

Design of an Online Monitoring System for Degrading Hardware Components Using Failure
Modes and Effects Analysis

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Abstract

A nuclear hybrid energy system, consisting of different energy subsystems such as nuclear, solar, and wind, involves frequent switching between different energy subsystems and between different controls. This can potentially lead to faster aging and failure of mechanical components. The increased usage of the turbine bypass system is considered to be the major difference between a nuclear hybrid energy system and a traditional nuclear power plant. Reliability analysis for designing such a complex system involves both high level fault propagation analysis at the conceptual design stage and low level failure prediction for specific components. The two main focuses of this thesis are: first to develop behavioral rules and functional failure logic for hardware components; and second to derive a degradation model of hardware components.

The behavioral rules and functional failure logic form the *BehaviorModel* of the function failure identification and propagation (FFIP) method. FFIP is an approach that can help designers at the conceptual design stage to identify which function(s) will be lost in a system and approximately when and where. The simulation results obtained using FFIP can serve as indicators for the designers to determine if the system is robust enough or if more safeguards/redundancies are necessary. Implementing the method will reduce redesign and maintenance costs in later design, implementation and operational stages.

The degradation model is a low level failure mode model that combines the effects of natural aging and frequent switching conditions. The model can be used for predicting components' failure due to specific failure modes that are described in the behavioral rules. The result can serve as an indicator for conducting repair actions and maintenance to minimize Operation & Maintenance (O&M) costs. Both the high level FFIP method and the low level degradation model are demonstrated for the turbine bypass system in the secondary loop of a hybrid nuclear power plant.

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Chapter 1 Introduction

1.1 Nuclear hybrid energy system

According to the U.S Energy Information Administration (EIA), the U.S fossil fuel share of energy consumption in 2015 was 67%.[1] Fossil fuels are still being heavily relied on, and this trend is unlikely to change even until 2040 according to the EIA. Furthermore, the Central Intelligence Agency reported that with today's rate of consumption of fossil fuels, petroleum would run out by 2052, natural gas by 2060, and then coal by 2088. No fossil fuel will remain by the next century. Besides the limited reserves of fossil fuel, massive consumption of fossil fuel also raises concerns about global warming and pollution. Therefore, there has been a growing interest in reducing fossil fuel consumption in the energy structure and in increasing the proportion of clean energy.

Renewable energy (e.g. wind, solar) has the potential for distributed generation. This feature can reduce the cost of electricity transportation. However, the availability for renewable energy fluctuates and is uncontrollable. Therefore, additional energy sources need to be coupled with renewable energy to produce a stable electricity generation profile [2]. Nuclear energy can serve this purpose. Nuclear energy, as a clean energy source, has low greenhouse gas emission, possesses high power density and baseload power supply with low fuel cost. It is desirable to develop a hybrid energy system that processes both renewable energy and nuclear energy to meet low carbon emission goals and to utilize renewable energy. The proposed hybrid energy system is shown in Figure 1.

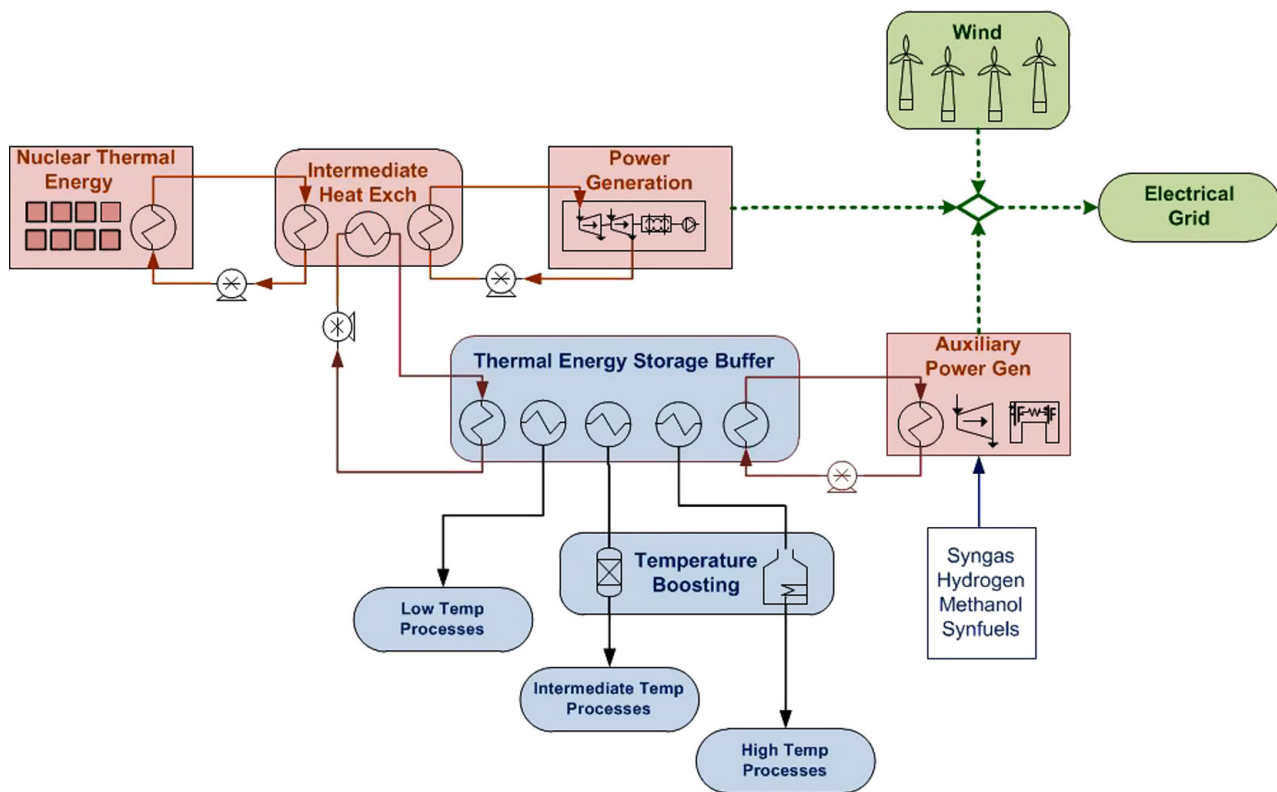


Figure 1 Schematic of a nuclear hybrid energy system [3]

As can be observed in the figure above, nuclear energy power generation and wind energy generation are coupled to provide stable power to the electric grid. Tight coupling of clean energy from different sources into a hybrid system has advantages compared to traditional power plants. Hybrid energy systems can reduce greenhouse gas emissions and provide highly reliable electricity, which is one of the major challenges for renewable power generation. High renewable energy penetration can reduce the cost of electricity transportation as well. Development of advanced energy systems that integrate low or zero-carbon generation sources will provide the needed energy sources with minimal impact on the environment. Integration of low-carbon resources in a manner that provides reliable energy supply is of particular importance in light of recent announcements on carbon reduction made by the Environmental Protection Agency.

Despite all the benefits mentioned above, nuclear hybrid energy systems also face challenges.

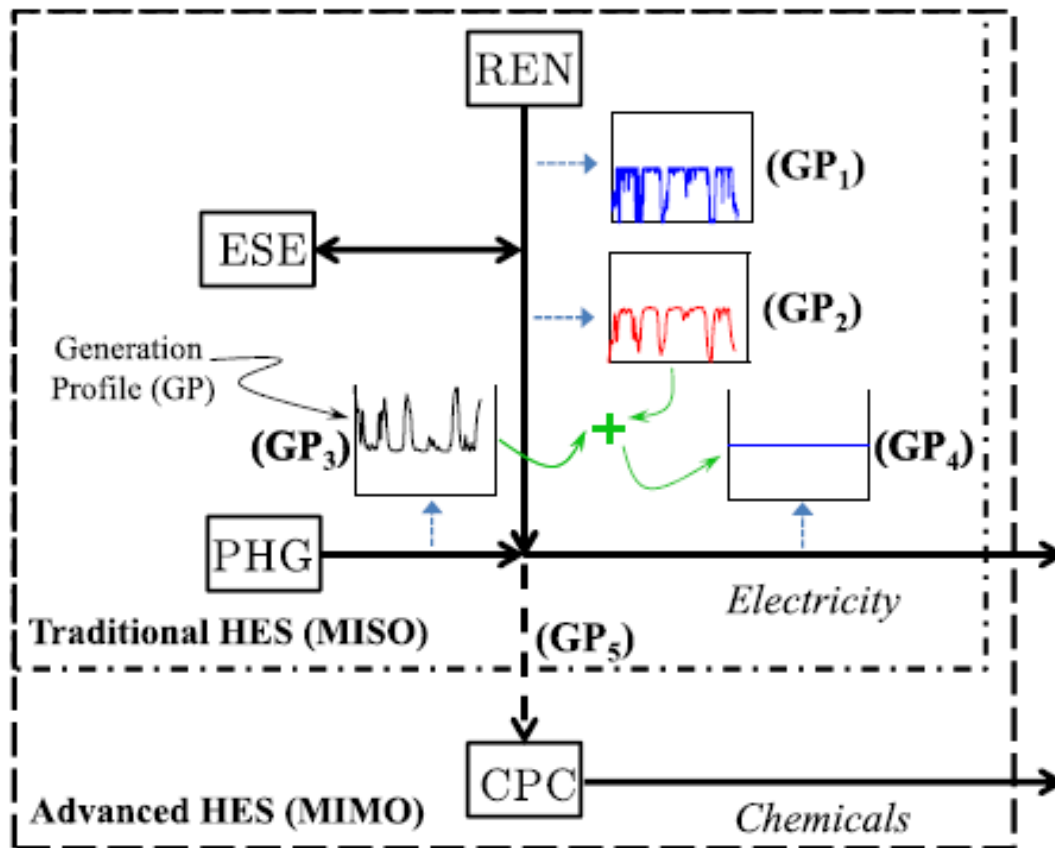


Figure 2 Distribution of renewable generation variability [4]

As can be seen from Figure 2, power generation from renewable energy sources (GP1) fluctuates. To supply stable power to the grid, the corresponding energy generation for the nuclear power plant (GP3) must fluctuate as well. For a nuclear power plant, the primary loop heat generation should remain constant. Thus, the frequent use of the turbine bypass line in the secondary loop is required to achieve the fluctuating power generation.

1.2 Reliability engineering

Reliability engineering is a field that studies the dependability of a product during its lifecycle. It focuses on the performance of the physical systems or functional objects [5]. The objective of reliability engineering analysis according to Patrick O'Connor in *Practical Reliability Engineering?* [6], is to:

- “1. To apply engineering knowledge and specialized techniques to prevent or to reduce the likelihood or frequency of failures.
2. To identify and correct the causes of failures that do occur, despite the efforts to prevent them.
3. To determine ways of coping with failures that do occur, if their causes have not been corrected.
4. To apply methods for estimating the likely reliability of new designs, and for analyzing reliability data.”

For the objectives stated above, the approaches for reliability analysis can be both quantitative and qualitative in nature.

Commonly used qualitative techniques for reliability analysis include failure mode and effects analysis (FMEA), hazard analysis, and fault tree analysis (FTA). An important quantitative approach in reliability engineering is to identify the reliability parameters and probability model that best describe the system's reliability behavior. However, due to the high degree of uncertainty in the quantitative analysis, a high-level qualitative analysis is also useful in reliability engineering.

In this thesis, both quantitative and qualitative methods are implemented to analyze the reliability performance at the component and nuclear hybrid energy system level.

1.3 Online monitoring system for a nuclear hybrid energy system

Online monitoring of an integrated energy system is a highly complex problem. Due to the nature of coupling electrical generation from different energy sources, the system dynamics will involve frequent switching between different energy systems and switching between different control systems. Frequent switching between the energy systems may lead to faster aging of the mechanical components and the sensors, leading to unprecedented shutdowns of one of the energy systems. Failure of an energy system can add an unexpected load on the nuclear power plant, increasing the likelihood of an accident. Nuclear power plant operation as a part of an integrated, hybrid energy system requires special operator training to understand the load distribution and expected dynamic power generation from the plant. Human error probability may increase in hybrid energy systems. To minimize the risk of component failure, control failure, human error, and to help improve the operator's ability to monitor the hybrid energy system, an advanced digital alarm system is required. A proposed online monitoring system is shown in Figure 3.

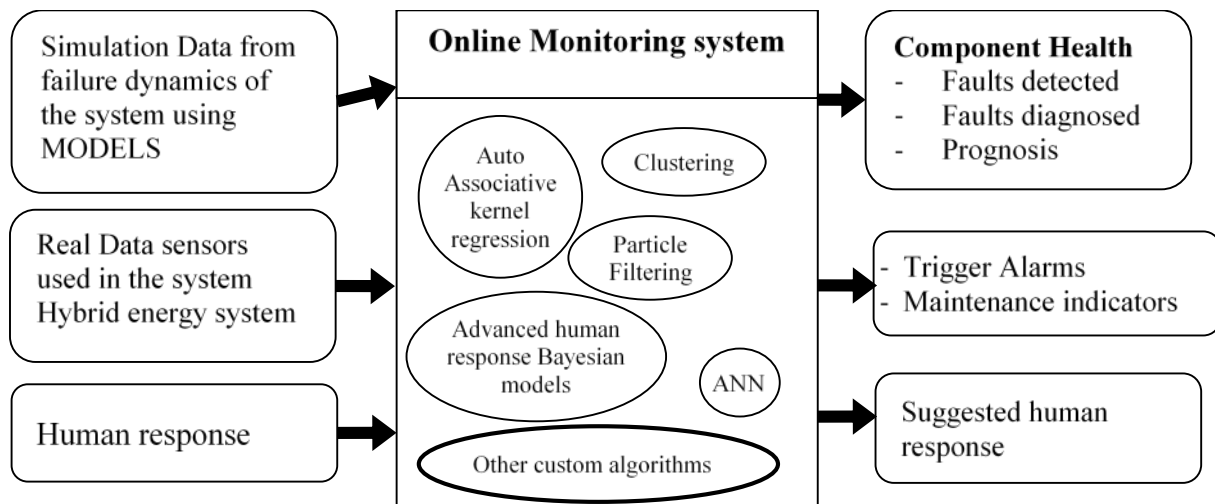


Figure 3 Proposed Online Monitoring System

The online monitoring system compares the data collected by various sensors in the secondary loop of the nuclear power plant to previously built models of the system. The models describe different manners that the system could behave such as nominal and faulty. The

comparison is implemented through existing data analysis algorithms and customized algorithms. In this way, the online monitoring system can classify the health status of each component and detect faults and failures. The alarm system can then be designed to respond appropriately to each detected fault and provide operational instructions. The operator should follow the instructions to conduct repair actions. In this way, the implementation of the online monitoring system can prevent future fault propagation. The customized algorithms will be both quantitative and qualitative, and will be able to communicate with other existing algorithms. The online monitoring system will be developed and verified using the simulation models for the integrated system. The main objective of this research is to provide models and rules for fault detection and fault diagnosis in the online monitoring system. The impact of system's duty cycles on aging degradation and reliability of the steam bypass system is the main concern for the study.

1.4 Research objectives

1. Develop the behavioral rules and functional failure logic for the components of interest in the online monitoring system.
2. Combine natural aging and degradation effects to derive a general degradation model.
3. Estimate the parameters of the degradation model for selected failure modes, e.g. leakage.

1.5 Thesis outline

The thesis is formed by four chapters. Chapter 1 introduces the topic of the thesis. Chapter 2 reviews concepts of fault failure identification and propagation (FFIP) to study fault propagation at the conceptual design stage. The associated behavioral rules and functional failure logic have been developed for components of interest.

Chapter 3 reviews the methodology of strength-stress interference and develops a degradation model to describe the general failure behavior. The specific failure mode of internal leakage of the turbine bypass valve is selected for study.

Chapter 4 summarizes this thesis and recommends some future work.

Chapter 2: Behavioral Rules and Functional failure logic for Hardware Components

2.1 Review of failure mode and effect analysis

This chapter discusses a qualitative approach to perform reliability analysis. There are several commonly used methodologies in reliability engineering for high level risk analysis. Two of the most used methods are failure mode and effect analysis (FMEA) and fault tree analysis (FTA). FMEA is mainly discussed since it is related to the Function Failure Identification and Propagation (FFIP), which is the method implemented in this chapter.

FTA is a top-down approach to analyze system failure which starts from the system's failure event or undesired state. It is a deductive approach from the system level failure to the component level failure to identify the possible root causes of a system's failure.

Unlike FTA, FMEA is an inductive, component level approach to identify failure. It is a systematic approach to identify what local and system level effects could be caused by the different types of failure modes of each component. A failure mode is defined as the manner in which the failure of a component manifests itself. It is the result of the corresponding failure mechanism. The local effect describes the low-level effects that the failure mode could cause. The intermediate level effect(s) describes the effect(s) at the intermediate level(s) that the failure mode could cause. The system level effect describes the effect at the system level that the failure mode could cause. For example, internal leakage is a failure mode for a throttle valve. This failure mode is the result of the failure mechanism of sealing material wearing out. The local effect is the air flow rate downstream of the throttle valve is higher than the designed value. The intermediate level effect is the air fuel cannot mix ideally in the throttle body. The system level effect is the engine knock will occur in the cylinder.

FMEA then assesses the risk by assigning a 1 to 10 rating scale for severity, for the probability that the failure will occur, and for detectability. Based on the rating grade, the risk level of the failure mode is determined. FMEA identifies how will a component fail, the manner that a fault occurs, and its local and higher level effects. Even though FMEA is an effective tool in analyzing systems' failure behavior there are several limitations. Primarily, the rating grades for severity, probability, and detectability are highly subjective. Experience with the physical system is required to make reasonable evaluations. The rating standard for different failure modes may not be consistent as well, since different database sources may

have different evaluation criteria towards the same failure mode. Another issue is that FMEA focuses on single-event initiators. There is no failure mode combination analysis in the traditional FMEA analysis.

2.2 Function failure identification and propagation (FFIP) approach for failure analysis

2.2.1 Introduction of FFIP

Integrated system failure analysis (ISFA) was previously developed by Chetan Mutha at The Ohio State University [8]. It is a design approach which can be used in the early stages of product design to identify potential system failures and fault propagation. The approach has the advantage of eliminating costly redesign in the later validation stages. The ISFA method integrates the Function Failure Identification and Propagation (FFIP) and Failure Propagation and Simulation Approach (FPSA). FFIP focuses on hardware failures. FPSA concentrates on software failures. For the scope of this thesis, only hardware failures are considered, therefore human errors and software faults are not considered as potential sources of failure.

Similar to FMEA, FFIP also uses a forward approach to conduct risk assessment. The simulation is based on a qualitative model, which fits the situation at the conceptual design stages where there still is uncertainty in the system design. FFIP is implemented during the conceptual design stage by modeling the system using different design views and by injecting a fault in a single or multiple components and traversing the design views systematically to determine the impact of the faults. The objective of FFIP is to identify the fault propagation that leads to the system's loss of function and modify the design accordingly.

FFIP uses a graphical approach such as Systems Modeling Language (SysML) to qualitatively analyze system's behavior. It estimates components' state based on state variables. Based on a graphical approach that reflects the physical layout of the system design, it is possible to inject multiple faults at the same time to study propagation and functional failure. This differs from the traditional FMEA analysis which was discussed in the previous section.

2.2.2 Structure of FFIP

Based on the definition of FFIP, the model consists of 4 blocks: *FunctionModel*, *ConfigurationFlowGraph*, *Flow*, and *BehaviorModel*, as shown in Figure 4.

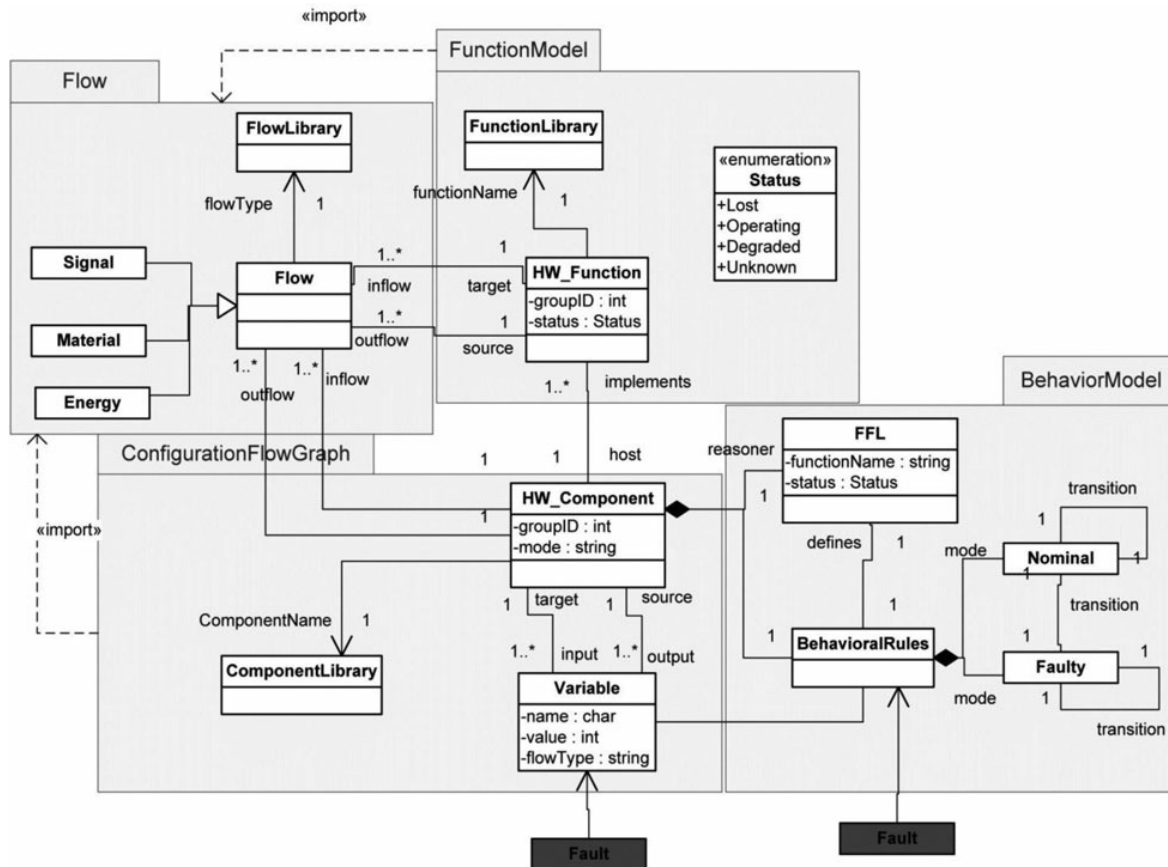


Figure 4 Structure of FFIP

The figure above demonstrates how the four blocks interact with each other.

Flow is the entity that is modified by functions as it passes through the system. For example, in a nuclear power plant steam is a type of *Flow* which is heated up and cooled down by the components it passes through.

FunctionModel includes the components' functions in the system and the way in which they interact. The inlet *Flow* is modified by the hardware's *FunctionModel* to become the outlet *Flow*. For example, the function for a valve is to regulate fluid flow; the function for a pipe is to transfer fluid flow. It should be noted that one component can have multiple functions. For example, a turbine bypass valve possesses two functions: regulate flow and de-superheat flow.

ConfigurationFlowGraph is the section that describes the physical layout of the system. *ConfigurationFlowGraph* imports the same *Flow* as *FunctionModel*, because functions are mapped into components using *Flow*; the model needs to be consistent in both component view and function view. Thus, the inlet and outlet *Flow* of a component must be the same inlet and outlet *Flow* for the function(s) that are hosted in that component.

A *BehavioralModel* is defined qualitatively for each hardware component. It possesses two portions: behavioral rules and functional failure logic (FFL). Behavioral rules are divided into nominal and faulty. Nominal is when a component is working properly. Faulty includes the components behaviors for each failure mode. FFL describes the relationship between a component's state and a function's state. The status of a function is evaluated based on its component behavior and the detected inlet and outlet *Flow*. If the component status is nominal, the outlet *Flow* matches the given inlet *Flow* through the defined function; otherwise, if the component status is faulty, the status of the function matches the predefined FFL. If the component's behavior is not described in the behavioral rules, the function status is unknown.

The objective of the FFIP method is to study fault propagation at a high level of abstraction. FFIP is conducted by behavioral simulation. To simulate the behavior of the system triggered by fault(s), predefined fault mode propagation is triggered. A fault mode propagation is defined based on the physical layout; it describes how a fault in one component affects that component and the downstream component that connects to it through *Flow*. The simulation is in discrete time, and qualitatively informs the user how a designed system would fail for the particular fault injection.

In this thesis, the analysis is based on the secondary loop of a nuclear power plant. To implement the FFIP technique, the components of interest must be identified, and the behavioral rules and functional failure logic for the system must be defined. In the last section of the chapter, a case study will be conducted using FFIP.

2.3 Behavioral Rules and Functional failure logic

2.3.1 Identify component of interest

The goal of the online monitoring system discussed in Chapter 1 is to monitor the secondary loop in a nuclear power plant to increase the reliability of the power plant.

Within the nuclear power plant, the main reliability concern is the steam turbine bypass system. The components of interest in the steam turbine bypass system are the turbine bypass valve, multifunction flowmeter, and steam pipeline. Behavioral rules and functional failure logic will be developed for these components.

2.3.2 Turbine bypass valve

A typical turbine bypass valve in a nuclear secondary loop is shown in Figure 5 [9].

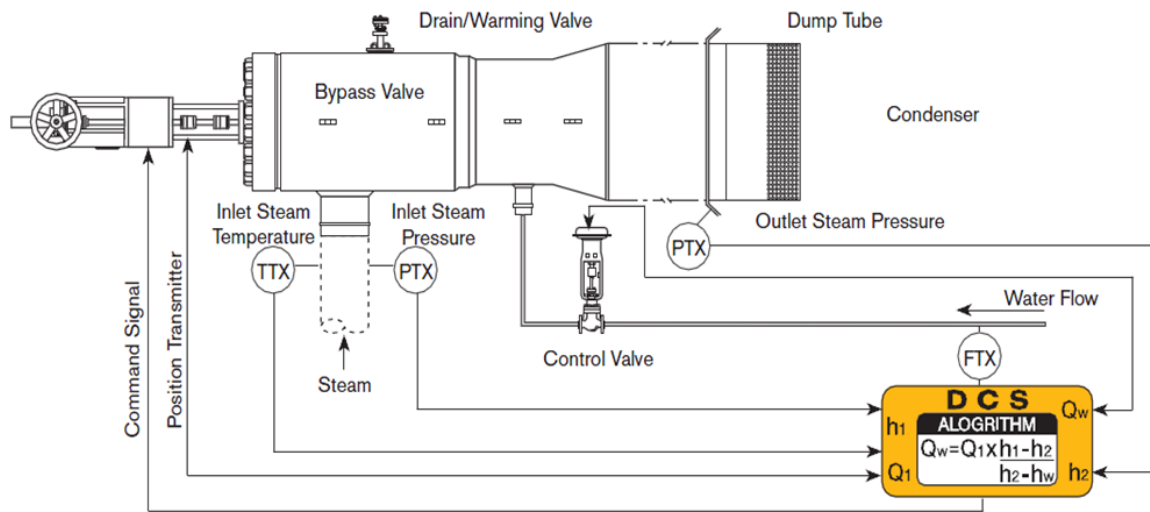


Figure 5 Turbine Bypass Valve Illustration

The turbine bypass valve is composed of two valves working together: a bypass valve and a spray water valve. The spray water valve injects cold water into the bypass valve to de-superheat the high temperature, high-pressure steam. The control logic for the water injection is also shown above. The failure of a spray water valve is usually caused by software faults. Since the software faults are outside the scope of this thesis, the spray water valve is deemed to be reliable. Therefore, the analysis for the turbine bypass valve only concerns the bypass valve.

The *Flow* for the component valve is steam, and the function of the valve is to regulate fluid flow and de-superheat fluid flow. Table 1 describes the components' behavior for each failure mode based on their input-output relationship. The behavioral rules in Table 1 are based on representing the physics of the component interactions at the conceptual stage. The input variables for the turbine bypass valve are the inlet flow rate, the inlet temperature, and the inlet amount of corrosion. The output variables are the outlet flow rate, the outlet temperature and the outlet amount of corrosion. The "Model" column in Table 1 contains variables that are suspected to contribute to the corresponding failure mode. The model does not indicate that the degradation process follows the mathematical relationship. Quantification requires more precise simulation and experimental data. The "Equivalent Behavior" column contains the behavior that the valve performs for each failure mode.

Table 1 Failure Modes for the Turbine Bypass Valve

Failure Mode	Model	Local Effect (With leakage inexplicit)	Equivalent Behavior
Nominal. Idle Nominal. Opening Nominal. Closing		<p>If $Q_{out} == Q_{in}$ AND $Q_{out} == Q_{out_nom}$ AND $P_{out} == (DD)*P_{in}$ AND $T_{out} == (DD)T_{in}$</p> <p>If $Q_{out}(t+1) == (+control)*Q_{out}(t)$ AND $Q_{out}(t+1) > Q_{out}(t)$ AND $T_{out} == (DD)T_{in}$</p> <p>If $Q_{out}(t+1) == (-control)*Q_{out}(t)$ AND $Q_{out}(t+1) < Q_{out}(t)$ AND $T_{out} == (DD)T_{in}$</p>	<p>If $PO(t+1) = PO(t)$</p> <p>If $PO(t+1) = (+control)*PO(t)$ AND $PO(t+1) > PO(t)$</p> <p>If $PO(t+1) = (-control)*PO(t)$ AND $PO(t+1) < PO(t)$</p>
Internal leakage. Idle Internal leakage. Opening Internal leakage. Closing	$\Delta T * \Delta P$ $* f * \sqrt{t}$	<p>If $Q_{out} > Q_{out_nom}$ AND $T_{out} > (DD)*T_{in}$</p> <p>If $Q_{out}(t+1) > (+control)*Q_{out}(t)$ AND $T_{out}(t+1) > (DD)*T_{in}(t+1)$</p> <p>If $Q_{out}(t+1) > (-control)*Q_{in}(t)$ AND $T_{out}(t+1) > (DD)*T_{in}(t+1)$</p>	<p>$PO_{min} > 0$; If(Nominal){ $PO(t+1) = PO(t)$ }</p> <p>If(Opening){ $PO(t+1) = (+control)*PO(t)$ AND $PO(t+1) > PO(t)$ }</p> <p>If(Closing){ $PO(t+1) = (-control)*PO(t)$ AND $PO(t+1) < PO(t)$ }</p>
Internal rupture. Idle Internal rupture. Opening Internal rupture. Closing	T_{max} $* P_{max}$ $* \Delta T * \Delta P$ $* f * \sqrt{t}$	<p>If $Q_{out} >> Q_{out_nom}$ AND $T_{out} >> (DD)*T_{in}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$</p> <p>If $Q_{out}(t+1) >> (+control)*Q_{out}(t)$ AND $T_{out}(t+1) >> (DD)*T_{in}(t+1)$ AND $Q_{corrosion_out} > Q_{corrosion_in}$</p> <p>If $Q_{out}(t+1) >> (-control)*Q_{in}(t)$ AND $T_{out}(t+1) >> (DD)*T_{in}(t+1)$ AND $Q_{corrosion_out} > Q_{corrosion_in}$</p>	<p>$PO_{min} >> 0$; $PO > PO_{in}$</p>
External leakage. Idle External leakage. Opening External leakage. Closing	T_{max} $* P_{max}$ $* \Delta T * \Delta P$ $* f * \sqrt{t}$	<p>If $Q_{out} < Q_{in}$ AND $T_{out} < (DD)*T_{in}$</p> <p>If $Q_{out}(t+1) < (+control)*Q_{out}(t)$ AND $T_{out}(t+1) < (DD)*T_{in}(t+1)$</p> <p>If $Q_{out}(t+1) < (-control)*Q_{in}(t)$ AND $T_{out}(t+1) < (DD)*T_{in}(t+1)$</p>	<p>$PO_{ByPass} > 0$</p>

External rupture. Idle	$\dot{m} * \Delta T$ $* \Delta P * f$ $* \sqrt{t}$	If $Q_{out} << Q_{in}$ AND $T_{out} << (DD) * T_{in}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$ If $Q_{out}(t+1) << (+control) * Q_{out}(t)$ AND $T_{out}(t+1) << (DD) * T_{in}(t+1)$ AND $Q_{corrosion_out} > Q_{corrosion_in}$ If $Q_{out}(t+1) << (-control) * Q_{in}(t)$ AND $T_{out}(t+1) << (DD) * T_{in}(t+1)$ AND $Q_{corrosion_out} > Q_{corrosion_in}$	$PO_{ByPass} >> 0$
External rupture. Opening			
External rupture. Closing			
Spurious operation	$\dot{m} * \Delta P * f$	IF else	

PO: position of valve; Q_{out} : outlet flow; Q_{in} : inlet flow; Q_{out_nom} : nominal output flow; +control: control signal to open the valve; -control: control signal to close the valve; P_{max} : maximum pressure; \hat{P} : estimated pressure; P' : actual pressure; T_{max} : maximum temperature; T_{out} : outlet temperature; T_{in} : inlet temperature; DD: de-superheat effect; \hat{T} : estimated temperature; T' : actual temperature; PO=0=fully closed; PO=1=fully open.

*To create equivalent behavior for external leakage/rupture, a bypass valve is set parallel to the main valve, the bypass valve excludes the amount of flow that is assumed to be lost in the loop.

Table 2 maps components' status to functions' status. Functions for the turbine bypass valve are to regulate flow and de-superheat the flow. The status for functions are defined as operating, degraded, lost, and unknown. Operating indicates that the component behavior is consistent with achieving the function. Degraded indicates that the function is not being fully performed. Lost indicates that the component is failing to perform the desired function entirely. The component's status has an influence on the function(s) that the component possesses, which is shown in Table 2. A change of the function status alters the outlet *Flow*, and affects all the components that the *Flow* goes through.

Table 2 Behavioral rules and Functional Failure Logic for the Turbine Bypass Valve

Input	Output	Functionalities	Behavioral rules	Functional failure logic
Q_{in} T_{in} $Q_{corrosion_in}$	Q_{out} T_{out} $Q_{corrosion_out}$	Regulate Flow De-superheated Flow	Mode == Nominal IF Local effect. Nominal Mode == Internal Leak IF Local effect. Internal leakage Mode == Internal Rupture IF Local effect. External leakage Mode == External Leakage IF Local effect. External leakage Mode == External Rupture IF Local effect. External Rupture Mode == Spurious operation IF Local effect. Spurious operation	IF mode == Nominal Then Regulate Fluid == O De-superheated Flow == O IF mode == Internal Leak Then Regulate Flow == D De-superheated Flow == D IF mode == Internal Rupture Then Regulate Flow == L De-superheated Flow == L IF mode == External Leakage Then Regulate Flow == D De-superheated Flow == D IF mode == External Rupture Then Regulate Flow == L De-superheated Flow == L IF mode == Spurious operation Then Regulate Flow == U De-superheated Flow == U

O: Operating; D: Degraded; L: Lost; U: Unknown

2.3.3 Multifunction flowmeter

A description of behavioral rules and functional failure logic for the multifunction flow meter are based on a description of Rosemount's compact orifice flow meters [10].

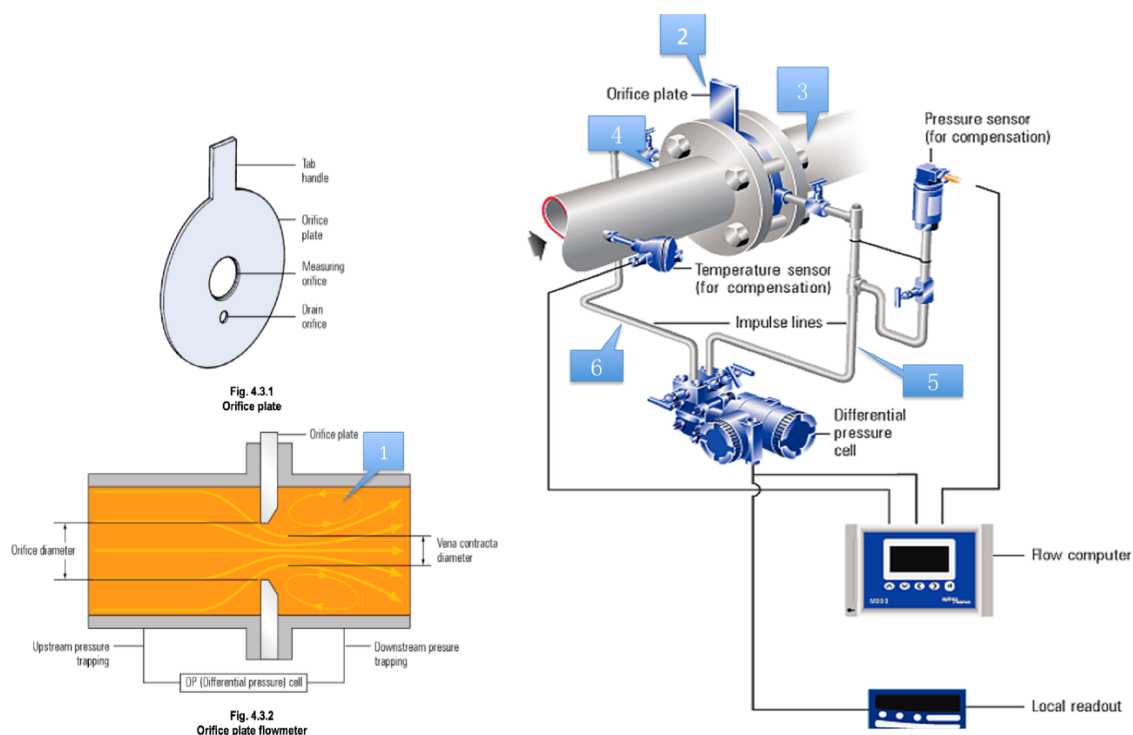


Figure 6 Rosemount Compact Orifice Flowmeters

The flow meter depicted in Figure 6 is an illustration for a flow meter that is commonly used in nuclear power plants. As can be seen from the figure above, an orifice plate is a thin plate with a hole at the center. When fluid flow goes through the orifice plate, the velocity of the flow increases due to the conservation of mass. Orifice flow meters use the pressure difference between the flow upstream and the flow downstream of the plate. The flow rate can be determined based on Bernoulli's equation and industry standard coefficients.

For simplicity, the flow rate can be expressed as shown in Equation 1.

$$Q = C * A \sqrt{2(P_1 - P_2) * \rho} \quad \text{Equation 1}$$

C: Flow meter coefficient A: Cross-section area for the orifice hole

P1: Upstream Pressure P2: Downstream Pressure

ρ : Density Q: Flow rate

Table 3 describes the flowmeter's behavior for each failure mode based on the input-output relationship. The input variable is the actual flow rate. The output variable is the detected flow rate. The "Location" column describes the location where the failure mode occurs.

Table 3 Failure Modes for the Flowmeter

Failure Modes		Model	Local Effect	Location
Normal			$Q_{detect} = Q_{actual} = Q_{nominal}$	
Fluid turbulence		$\dot{m} * Re * \Delta P$	$Q_{detect} = Q_{actual} + noise$ $Q_{actual} = Q_{nominal}$	[1]
Plate fault	Orifice plate crack	$\dot{m} * T_{max} * P_{max} * f * \Delta T * \Delta P * \sqrt{t}$	$Q_{detect} < Q_{actual}$ $Q_{actual} < Q_{nominal}$	[2]
	Orifice abrasion	$\dot{m} * f * \sqrt{t}$	$Q_{detect} < Q_{actual}$ $Q_{actual} < Q_{nominal}$	[2]
	Orifice plate lugging	$T_{max} * \Delta T * \Delta P * f * \sqrt{t} * \eta$	If (total plugging) { $Q_{actual} = 0$; $Q_{detect} = Q_{large} \gg Q_{actual}$; } else { $Q_{detect} < Q_{actual}$ } $Q_{actual} < Q_{nominal}$	[2]
Nearby pipe fault	Flow Pipe leakage upstream	$T_{max} * P_{max} * \Delta T * f * \Delta P * \sqrt{t}$	$Q_{detect} < Q_{actual}$ $Q_{actual} < Q_{nominal}$	[4]
	Flow Pipe leakage downstream	$T_{max} * P_{max} * \Delta T * f * \Delta P * \sqrt{t}$	$Q_{detect} > Q_{actual}$ $Q_{actual} < Q_{nominal}$	[3]
	Upstream Pressure taps leak	$T_{max} * P_{max} * \Delta T * f * \Delta P * \sqrt{t}$	$Q_{detect} < Q_{actual} = Q_{nominal}$	[6]
	Downstream Pressure taps leak	$T_{max} * P_{max} * \Delta T * f * \Delta P * \sqrt{t}$	$Q_{detect} > Q_{actual} = Q_{nominal}$	[5]
Circuit fault	short circuit	$\dot{m} * f * \sqrt{t}$	$Q_{detect} = \text{maximum};$	
	open circuit	$\dot{m} * f * \sqrt{t}$	$Q_{detect} = 0;$	
Fails to operate		$\dot{m} * \Delta T * f * \Delta P * \sqrt{t}$	$Q_{detect} = 0$	

\dot{m} : Mass flow rate; Re : Remold number at the orifice plate; ΔP : Pressure difference across the orifice plate; ΔT : Temperature difference across the orifice plate; f : Demand for the turbine bypass; T_{max} : Maximum temperature across the flow meter; P_{max} : Maximum pressure across the flow meter; t : time after operation; Q_{actual} : Actual flow rate; Q_{detect} : Flow rate detected by the flow meter; $Q_{nominal}$: Nominal flow rate; $Q_{large} = C * A_2 \sqrt{2(P_1 - P_{ref}) * \rho}$

Table 4 maps the flowmeter's status to its functions' status. A flow meter is used to measure the fluid flow rate, thus, when the meter can report the actual flow rate the meter is in operating status. When the meter cannot reflect the real flow rate, the meter has lost its function. There is no intermediate status such as "degraded" for flow meter.

Table 4 Behavioral rules and Functional Failure Logic for the Flow Meter

Input	Output	Functionalities	Behavioral rules	Functional failure logic
Q _{in} P _{in}	Q _{out} P _{out}	Measure flow	Mode == Normal IF Local effect. Normal Mode == Plate fault IF Local effect. Plate fault Mode == Nearby pipe fault IF Local effect. Nearby pipe fault Mode == Circuit Fault IF Local effect. Circuit fault Mode == Fails to Operate IF Local effect. Fails to operate	IF mode == Nominal Then Measure Flow == O IF mode == Plate Fault Then Measure Flow == L IF mode == Nearby Pipe Fault Then Measure Flow == L IF mode == Circuit Fault Then Measure Flow == L IF mode == Fails to operate Then Measure Flow == L

O: Operating; D: Degraded; L: Lost; U: Unknown

As can be seen from the table above, multiple failure modes have the same local effect. Determining the exact failure mode of the flow meter is not necessary. As long as symptoms are detected through the online monitoring system, the appropriate repair operations will be suggested, and the failure should be repaired.

2.3.4 Steam pipeline

Pipes are used to transfer flow in a power plant. Ideally, a flow's property should be the same along the pipeline. To monitor the performance of a pipeline, sensors are placed to detect the variable of interest for the flow within the pipeline. Figure 7 is an example of using sensors to detect leakage in a pipe.

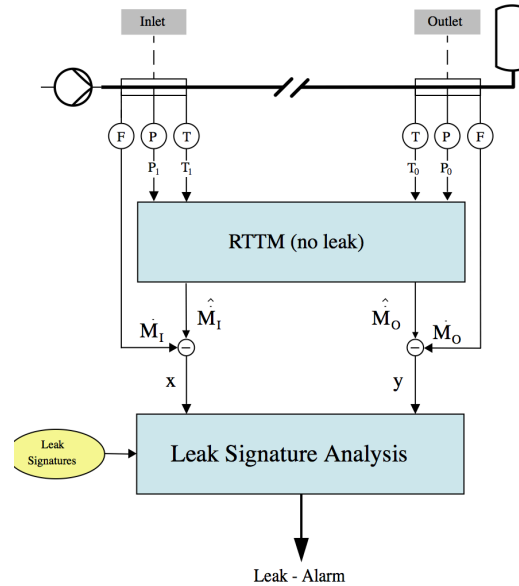


Figure 7 Pipe Detection Method Illustration [11]

Table 5 describes the pipeline's behavior for each failure mode based on the input-output relationship. The input variables are the inlet flow rate, inlet temperature, and the inlet corrosion. The output variables are the outlet flow rate, the outlet temperature and the outlet corrosion.

Table 5 Failure Modes for the Pipe Line

Failure Mode	Model	Local Effect
Nominal		If $T_{out} = T_{in}$ AND $Q_{out} = Q_{in}$ AND $Q_{corrosion_out} = Q_{corrosion_in}$
Leakage	$T_{max} * P_{max} * \Delta T * \Delta P * f * \sqrt{t}$	If $T_{out} < T_{in}$ AND $Q_{out} < Q_{in}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$
Plugging	$T_{max} * P_{max} * \Delta T * \Delta P * f * \sqrt{t} * \eta$	If $T_{out} > T_{in}$ AND $Q_{out} < Q_{in}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$
Rupture	$T_{max} * P_{max} * \Delta T * \Delta P * f * \sqrt{t}$	If $T_{out} < T_{in}$ AND $Q_{out} \ll Q_{in}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$

η : Impurity of the flow; t : Time after operation; T_{max} : Maximum temperature in the pipe; P_{max} : Maximum pressure in the pipe; f : Demand for the turbine bypass line T_{out} : Outlet temperature; T_{in} : Inlet temperature; Q_{out} : Outlet flow rate; Q_{in} : Inlet flow rate; $Q_{corrosion_out}$: Outlet corrosion material; $Q_{corrosion_in}$: Inlet corrosion material; ΔP : Pressure difference across the pipe; ΔT : Temperature difference across the pipe;

Table 6 maps pipe's status to its functions' status.

Table 6 Behavioral rules and Functional Failure Logic for the Pipeline

Input	Output	Functionalities	Behavioral rules	Functional failure logic
Q_{in} T_{in} $Q_{corrosion_in}$	Q_{out} T_{out} $Q_{corrosion_out}$	Transfer flow	<p>Mode == Nominal</p> <p>IF Local effect. Nominal</p> <p>Mode == Leakage</p> <p>IF Local effect. Leakage</p> <p>Mode == Rupture</p> <p>IF Local effect. Rupture</p> <p>Mode == Plugging</p> <p>IF Local effect. plugging</p>	<p>IF mode == Nominal</p> <p>Then Transfer Fluid == O</p> <p>IF mode == Leakage</p> <p>Then Transfer Flow == D</p> <p>IF mode == Rupture</p> <p>Then Transfer Flow == L</p> <p>IF mode == Plugging</p> <p>Then Transfer Flow == D</p>

O: Operating; D: Degraded; L: Lost; U: Unknown

As shown in the table above, the only failure mode of a pipe that can cause the loss of function "transfer flow" is the rupture.

If a pipe connects *Flow* from more than one pipe, then there are multiple inlet variables that describe the same property of inlet *Flow* from different components. Table 7 and Table 8 show the behavioral rules and FFL for a pipe with 2 inlet *Flow*.

Table 7 Behavioral Rules for the Pipeline with 2 Inlet Flows

Failure Mode	Local Effect
Nominal	IF $Q_{out} = Q_{in1} + Q_{in2}$ AND $Q_{corrosion_out} = Q_{corrosion_in}$
Leakage	IF $Q_{out} < Q_{in1} + Q_{in2}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$ AND $[t(T_{in1} \neq T_{in2}) > t_{pl_cri}]$
Plugging	IF $T_{out} > \max(T_{in1}, T_{in2})$ AND $Q_{out} < Q_{in1} + Q_{in2}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$
Rupture	IF $Q_{out} \ll Q_{in1} + Q_{in2}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$ AND $[t(T_{in1} \neq T_{in2}) > t_{pr_cri}]$
Corrosion	IF $Q_{out} = Q_{in1} + Q_{in2}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$ AND $[t(T_{in1} \neq T_{in2}) > t_{pc_cri}]$

Table 8 FFL for Pipeline with 2 Inlet Flows

Input	Output	Functionalities	Behavioral rules	Functional failure logic
Q_{in_1} T_{in_1} Q_{in_2} T_{in_2} $Q_{corrosion_in}$	Q_{out} T_{out} $Q_{corrosion_out}$	Transfer flow	<p>Mode == Nominal</p> <p>IF Local effect. Nominal</p> <p>Mode == Leakage</p> <p>IF Local effect. Leakage</p> <p>Mode == Rupture</p> <p>IF Local effect. Rupture</p> <p>Mode == Plugging</p> <p>IF Local effect. plugging</p> <p>Mode == Corrosion</p> <p>IF Local effect. Corrosion</p>	<p>IF mode == Nominal</p> <p>Then Transfer Fluid == O</p> <p>IF mode == Leakage</p> <p>Then Transfer Flow == D</p> <p>IF mode == Rupture</p> <p>Then Transfer Flow == L</p> <p>IF mode == Plugging</p> <p>Then Transfer Flow == D</p> <p>IF mode == Corrosion</p> <p>Then Transfer Flow == D</p>

$t(T_{in1} \neq T_{in2})$: accumulate time unit that $T_{in1} \neq T_{in2}$; t_{pr_cri} : critical time to trigger pipeline corrosion;
 t_{pl_cri} : critical time to trigger pipeline leakage; t_{pr_cri} : critical time to trigger pipeline rupture; Q_{in_i} :
inlet flow from upstream component i; Q_{out} : outlet flow; T_{in_i} : inlet temperature from upstream
component i; T_{out} : outlet temperature; $Q_{corrosion_in}$: inlet corrosion; $Q_{corrosion_out}$: outlet corrosion;

2.4 Case study

2.4.1 Turbine bypass system layout

In this section a case study is demonstrated as an application of the FFIP method to the secondary side of the plant used in the context of a nuclear hybrid energy system. The online monitoring system focuses on the secondary loop of the nuclear power plant. A typical secondary loop in a nuclear power plant in Westinghouse designs [12] can be simplified as shown in Figure 8. [13]

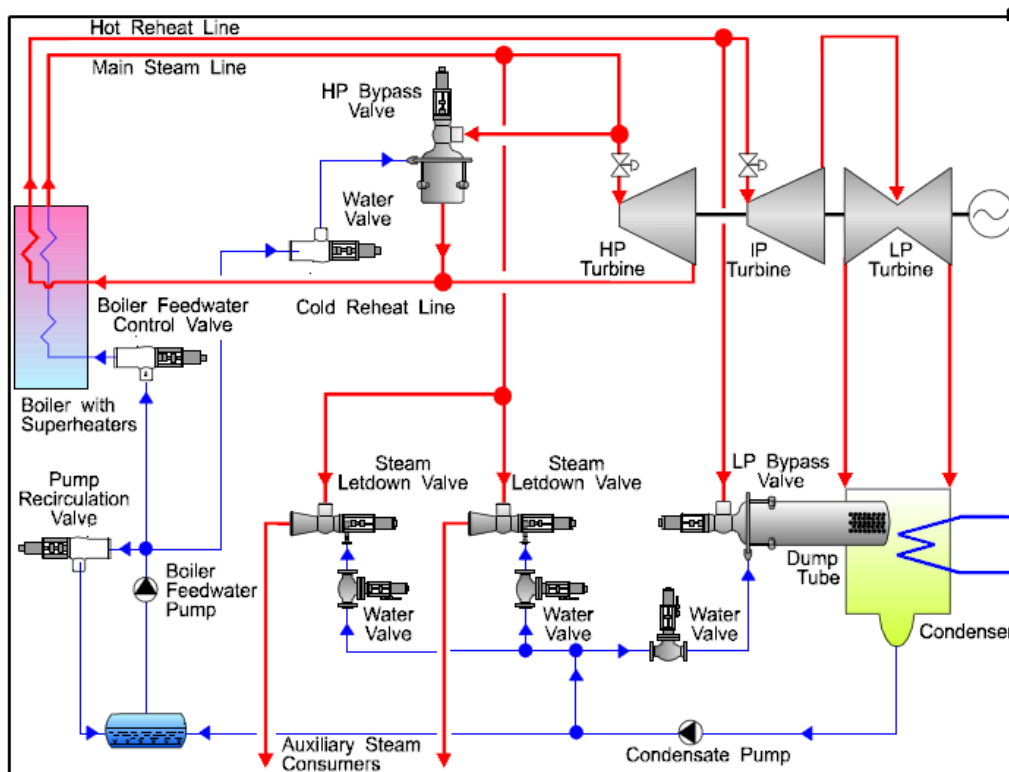
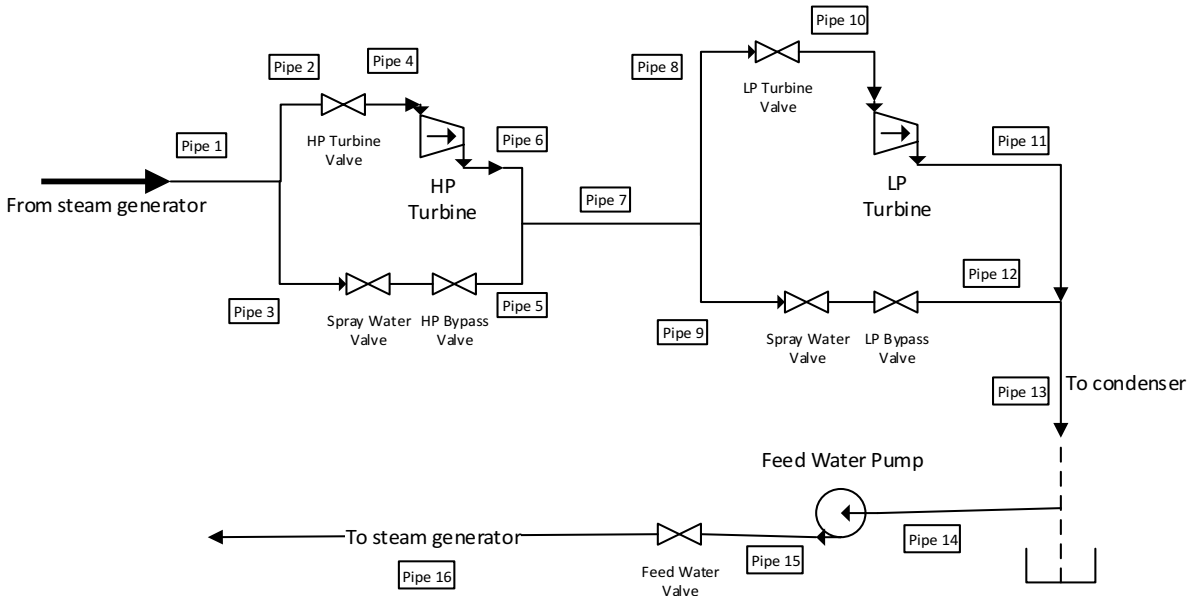


Figure 8 Typical Secondary Loop in Nuclear Power Plant

It should be noted that the secondary loop above also contains a reheat line, which can increase the energy conversion efficiency but is not necessary for a turbine bypass system. The steam that comes out of the steam generator (boiler) passes through 3 stage turbines that generate power and 3 stage turbine bypass lines that go into the condenser. After the steam from the turbine line and the turbine bypass line mix and go to the condenser, the steam goes back to the steam generator from the condenser through the feedwater line.

The objective of the case study in this section is to demonstrate the application of the FFIP method within the context of a nuclear hybrid energy system. Since the process for the high pressure, intermediate pressure and low pressure bypass segments are similar, the turbine bypass system is reduced into a 2 stage bypass system for simplicity as shown in Figure 9.



HP: High-pressure LP: Low pressure

Figure 9 Two Stage Turbine Bypass System

There are two turbine lines and two turbine bypass lines in the system above. The steam generator has three functions: storing steam, heating steam, and supplying heated steam to the rest of the system. Superheated steam comes out of the steam generator and goes through Pipe1 and is split into two parts. One portion goes to the high-pressure turbine line and the other goes to the high-pressure turbine bypass line. There is a stop valve in front of the turbine. If the turbine degrades, the stop valve would close and allow a human operator to conduct repair and maintenance. The steam that comes out of the high-pressure turbine and the steam that comes out of the high-pressure turbine bypass valve have similar properties, and the two parts of steam mix through Pipe7 and go into the second stage of the turbine bypass system. The low pressure stage works in the same way as the high pressure stage. After the steam comes out of the low

pressure stage, the mixed steam goes into the condenser and is condensed into liquid form. Then the *Flow* changes from steam to water and is pumped back to the steam generator through the feedwater line.

Condenser, turbine and feed water pump are not in the turbine bypass line. Thus, their behavioral rules and function failure logic are not fully developed. However, these components are essential for the secondary loop of a nuclear power plant to operate properly. For the scope of this case study, simplified behavioral rules and the corresponding function failure logic for these components are shown in Table 9.

Table 9 Simplified Behavioral Rules and Function Failure Logic for the Turbine, the Condenser and the Pump

Component	Input	Output	Functionalities	Behavioral rules	Functional failure logic
Turbine	Q_{in} T_{in} $Q_{corrosion_in}$	Q_{out} T_{out} $Q_{corrosion_out}$	Generator power De-superheat flow	Mode == Nominal IF $Q_{out} = Q_{in}$ AND $T_{out} = (DD)T_{in}$ AND $t(Q_{corrosion_in} > 0) \leq t_{bc_cri}$ Mode == Blade Corrosion IF $Q_{out} = Q_{in}$ AND $Q_{corrosion_out} > Q_{corrosion_in}$ AND $t(Q_{corrosion_in} > 0) > t_{bc_cri}$ Mode == Shut Down IF $Q_{in} = 0$	IF mode == Nominal Then Generator power == 0 De-superheat flow == 0 IF mode == Blade Corrosion Then Generator power == D De-superheat flow == D IF mode == Shut Down Then Generator power == L De-superheat flow == L
Condenser	Q_{in} T_{in} $Q_{corrosion_in}$	Q_{out} T_{out} $Q_{corrosion_out}$	Condense flow	Mode == Nominal IF $Q_{corrosion_in} = Q_{corrosion_out}$ AND $T_{out} = (DD)T_{in}$ AND $t(Q_{corrosion_in} > 0) \leq t_{bc_cri}$ Mode == Tube Corrosion IF $Q_{corrosion_out} > Q_{corrosion_in}$ AND $t(Q_{corrosion_in} > 0) > t_{bc_cri}$ Mode == Tube Break IF $Q_{corrosion_out} > Q_{corrosion_in}$ AND $Q_{out} > Q_{in}$ AND $t(Q_{corrosion_in} > 0) > t_{tb_cri} + t_{bc_cri}$	IF mode == Nominal Then Condense flow == 0 IF mode == Tube Corrosion Then Condense Flow == D IF mode == Tube Break Then Condense flow == L

Feed Water Pump	Q_{in} P_{in} $Q_{corrosion_in}$	Q_{out} P_{out} $Q_{corrosion_out}$	Increase Pressure Supply Flow	Mode==Nominal IF $Q_{out} = Q_{in}$ AND $P_{out} = (IP)P_{in}$ AND $Q_{corrosion_out} = Q_{corrosion_in}$ AND $t(Q_{corrosion_in} > 0) \leq t_{mc_cri}$ Mode==Outlet Pressure Low IF $Q_{out} = Q_{in}$ AND $P_{out} \leq (IP)P_{in}$ AND $Q_{corrosion_out} = Q_{corrosion_in}$ Mode== Motor Corrosion IF $Q_{corrosion_out} > Q_{corrosion_in}$ AND $t(Q_{corrosion_in} > 0) > t_{mc_cri}$	IF mode == Nominal Then Increase Pressure==O Supply Flow==O IF mode == Outlet Pressure Low Then Increase Pressure==D Supply Flow==O IF mode == Motor Corrosion Then Increase Pressure==L Supply Flow==L
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Q_{in} : Inlet flow rate; Q_{out} : Outlet flow rate; P_{in} : Inlet pressure; P_{out} : Outlet temperature; T_{in} : Inlet temperature; T_{out} : Outlet temperature; DD: De-superheat effect;
 $Q_{corrosion_in}$: Amount of corrosion at the inlet; $Q_{corrosion_out}$: Amount of corrosion at the outlet; IP: Increase pressure effect; t_{mc_cri} : critical time to trigger feed water pump motor corrosion failure mode; t_{tc_cri} : critical time to trigger condenser tube corrosion failure mode; t_{tb_cri} : critical time to trigger condenser tube break failure mode;

2.4.2 Function diagram for the turbine bypass system

The behavioral rules defined in section 2.3 will be implemented in this section. Figure 10 describes the functions of each component.

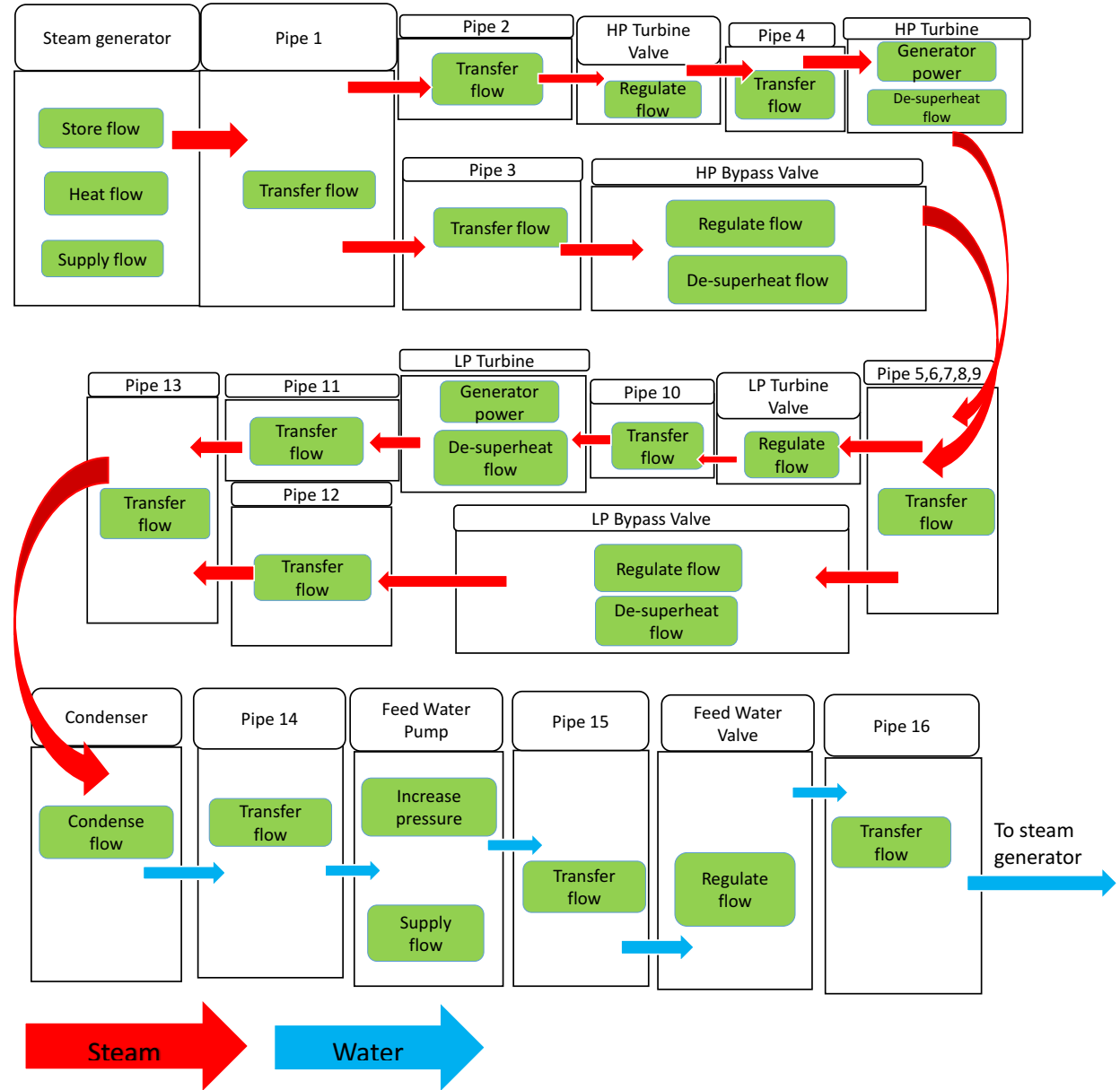


Figure 10 Function Diagram for the 2 Stage Turbine Bypass System

The function diagram above describes how the *Flow* connects each function in the system. The function diagram shows the mapping between functions and components. Fault propagation simulation can be conducted by injecting a fault into one or more components, and then studying

how the system's behavior changes due to the change of status of the components in the configuration diagram shown in Figure 9. The effect on functions can be studied using the function diagram. This shows one of FFIP's advantages against FMEA; FFIP allows the injection of multiple faults at the same time and the observation of the combined effect on the system.

Functions for the system are determined in the system requirements. For this application, we define the system's function to be "condense flow from the steam generator" and "supply flow to the steam generator". Thus, the system failure is defined as the function loss of either the feed water pump's "supply flow" or the condenser's "condense flow".

2.4.3 Failure Mode Transition Description

For the turbine bypass system described in the previous section, let us assume that the pipeline is in a "nominal" mode. If the inlet temperature is not uniform and this situation persists for more than a critical time period $t_{pc-cor} = 50 \text{ time units}$, the pipeline will transition from a "nominal" mode to a "corrosion" mode. A pipeline in a "corrosion" mode will lead to its function "transfer flow" to transition from a "operating" to a "degraded" status and bring corrosion into the rest of the system.

Let us assume that the turbine (high pressure or low pressure) is in a "nominal" mode. If the inlet corrosion flow $Q_{corrosion_in}$ is greater than 0 and this situation persists for more than a critical time period $t_{bc-cri} = 5 \text{ time units}$, then the turbine will transition to a "blade corrosion" mode. A turbine in a "blade corrosion" mode will lead to its function "generate power", and "de-superheat flow" transition to a "degraded" status. The "degraded" function(s) of a turbine leads to the shutdown of the upper stream turbine valve to ensure safety and conduct repair actions. Since the turbine valve is closed, the inlet flow to the turbine is 0, the turbine will transition to a "shut down" mode and the functions "generate power" and "de-superheat flow" are in a "lost" status. This case study does not consider repair actions, thus once the turbine valve shuts down, it stays closed and is not subject to any failure mode because it is reasonable to assume an always closed valve to be reliable.

Let us assume that the condenser is in a “nominal” mode. If there is corrosion at the inlet of the condenser and this situation persists for more than a critical time period $t_{cc-cri} = 10 \text{ time units}$, the condenser will transition to a “tube corrosion” mode and its function “condense flow” will switch to a “degraded” status. Once the condenser is in a “tube corrosion” mode, if the inlet corrosion flow $Q_{corrosion_in}$ is still greater than 0 and the situation persists for more than a critical time period $t_{tb-cri} = 15 \text{ time units}$, The condenser will transition to from a “tube corrosion” mode to a “tube break” mode and its function “condense flow” switches to a “lost” status. The loss of function “condense flow” leads to the loss of system’s functionality.

Let us assume that the feed water pump is a “nominal” mode. If there is corrosion at the inlet of the feed water pump and this situation persists for more than a critical time period $t_{mc-cri} = 20 \text{ time units}$. The mode of the feed water pump transitions to a “motor corrosion” mode and leads its function “supply flow” and “increase pressure” into a “lost” status. The loss of function “supply flow” leads the system to lose its functionality.

A change of a component’s function status changes the output variables and affects the downstream components. However, a power plant consists of many components, thus, the downstream components will not be affected immediately after the upper stream functions degrade. Let us assume the travel speed for the *Flow* is 1 component set/time unit. A component set is defined based on the CFG of the plant. For the system discussed in this section, assume Pipe1 is a component set. Pipe2, HP Turbine Valve, Pipe4, HP Turbine, Pipe6, and Pipe7 together is a component set; Pipe3, Spray Water Valve, HP Bypass Valve, Pipe5 and Pipe7 together is a component set. Similarly, Pipe8, LP Turbine Valve, Pipe10, LP Turbine, Pipe11 and Pipe13 together is a component set; Pipe9, Spray Water Valve, LP Bypass Valve, Pipe12, and Pipe13 together is a component set. The rest of the system, Condenser, Pipe14, Feed Water Pump, Pipe15, Feed Water Valve, and Pipe 16 together is a component set.

2.4.4 Simulation for Fault Propagation

The most significant feature of a nuclear hybrid energy system compared to a traditional nuclear power plant is the frequency of use of the turbine bypass system. Consider a load loss of

20% in the other portion of the hybrid energy system. The additional load will increase the usage of the turbine bypass line in the nuclear power plant. Since the load keeps changing, the turbine bypass valve will be opened and closed periodically, the event examined in this section makes the turbine bypass valve leaking. It will be shown that after an internal leakage fault is injected into the high pressure turbine bypass valve, the feed water pump eventually fails and the system loses its function entirely.

The state execution simulation begins at time unit 1. All components are assumed to be in “nominal” mode, also assume there is no corrosion in the system. According to FFL, all component’s functions are in “operating” status. Thus, the system function is “operating”.

Table 10 and 11 show the execution of the simulation at time unit 6 and time unit 56. The results demonstrate the logic of implementing the behavioral rules and FFL to conduct the fault propagation in the case study.

Table 10 System Behavior at Time Unit 6

Component	Mode	Inlet Flow	Outlet Flow	Behavior	Function	Status
HP TBV	Internal leakage	Q_{in_HPTBV}	Q_{out_HPTBV}	$Q_{out_HPTBV} > Q_{out_nom_HPTBV}$	TF	D
		T_{in_HPTBV}	T_{out_HPTBV}	$T_{out_HPTBV} > (DD) * T_{in_HPTBV}$	DF	D
		$Q_{corrosion_in_HPTBV}$	$Q_{corrosion_out_HPTBV}$	$Q_{corrosion_out_HPTBV} = Q_{corrosion_in_HPTBV}$		
Pipe5	Nominal	$Q_{in_P5} = Q_{out_HPTBV}$	Q_{out_P5}	$Q_{out_P5} = Q_{in_P5}$	TF	O
		$T_{in_P5} = T_{out_HPTBV}$	T_{out_P5}	$T_{out_P5} = T_{in_P5}$		
		$Q_{corrosion_in_P5} = Q_{corrosion_out_HPTBV}$	$Q_{corrosion_out_P5}$	$Q_{corrosion_out_P5} = Q_{corrosion_in_P5}$		
Pipe6	Nominal	Q_{in_P6}	Q_{out_P6}	$Q_{out_P6} = Q_{in_P6}$	TF	O
		T_{in_P6}	T_{out_P6}	$T_{out_P6} = T_{in_P6}$		
		$Q_{corrosion_in_P6}$	$Q_{corrosion_out_P6}$	$Q_{corrosion_out_P6} = Q_{corrosion_in_P6}$		
Pipe7	Nominal	$Q_{in_1_P7} = Q_{out_P6}$	Q_{out_P7}	$[t(T_{in1_P7} \neq T_{in2_P7}) = 1 \leq t_{pc_crit}]$	TF	O
		$T_{in_1_P7} = T_{out_P6}$	T_{out_P7}	$Q_{out_P7} = Q_{in_1_P7} + Q_{in_2_P7}$		
		$Q_{in_2_P7} = Q_{out_P5}$	$Q_{corrosion_out_P7}$	$Q_{corrosion_out_P7} = Q_{corrosion_in_P7}$		
		$T_{in_2_P7} = T_{out_P5}$				
		$Q_{corrosion_in_P7}$				
		$= Q_{corrosion_out_P6} + Q_{corrosion_out_P5}$				

Table 9 System Behavior at Time Unit 56

Component	Mode	Inlet Flow	Outlet Flow	Behavior	Function	Status
HP TBV	Internal leakage	Q_{in_HPTBV}	Q_{out_HPTBV}	$Q_{out_HPTBV} > Q_{out_nom_HPTBV}$	TF	D
		T_{in_HPTBV}	T_{out_HPTBV}	$T_{out_HPTBV} > (DD) * T_{in_HPTBV}$	DF	D
		$Q_{corrosion_in_HPTBV}$	$Q_{corrosion_out_HPTBV}$	$Q_{corrosion_out_HPTBV} = Q_{corrosion_in_HPTBV}$		
Pipe5	Nominal	$Q_{in_P5} = Q_{out_HPTBV}$ $T_{in_P5} = T_{out_HPTBV}$ $Q_{corrosion_in_P5} = Q_{corrosion_out_HPTBV}$	Q_{out_P5} T_{out_P5} $Q_{corrosion_out_P5}$	$Q_{out_P5} = Q_{in_P5}$ $T_{out_P5} = T_{in_P5}$ $Q_{corrosion_out_P5} = Q_{corrosion_in_P5}$	TF	O
Pipe6	Nominal	Q_{in_P6} T_{in_P6} $Q_{corrosion_in_P6}$	Q_{out_P6} T_{out_P6} $Q_{corrosion_out_P6}$	$Q_{out_P6} = Q_{in_P6}$ $T_{out_P6} = T_{in_P6}$ $Q_{corrosion_out_P6} = Q_{corrosion_in_P6}$	TF	O
Pipe7	Corrosion	$Q_{in_1_P7} = Q_{out_P6}$ $T_{in_1_P7} = T_{out_P6}$ $Q_{in_2_P7} = Q_{out_P5}$ $T_{in_2_P7} = T_{out_P5}$ $Q_{corrosion_in_P7}$ $= Q_{corrosion_out_P6} + Q_{corrosion_out_P5}$	Q_{out_P7} T_{out_P7} $Q_{corrosion_out_P7}$	$[t(T_{in1_P7} \neq T_{in2_P7}) = 51 > t_{pc_crt}]$ $Q_{out_P7} = Q_{in_1_P7} + Q_{in_2_P7}$ $Q_{corrosion_out_P7} > Q_{corrosion_in_P7}$	TF	D

$Q_{corrosion_in_i}$: corrosion at the inlet of the i-th component; $Q_{corrosion_out_i}$: corrosion at the outlet of the i-th component; Q_{in_i} : inlet flow rate of i-th component; Q_{out_i} : outlet flow rate of i-th component; T_{in_i} : inlet temperature of i-th component; T_{out_i} : outlet temperature of i-th component; $t(T_{in1} \neq T_{in2})$: accumulate time that inlet temperature is not uniformly distributed; t_{pc_crt} : critical time to trigger pipe corrosion failure mode

At time unit 6 the “internal leakage” failure mode is injected into the high pressure turbine bypass valve. This allows us to represent a potential effect of the frequent opening and closing of the turbine bypass valve. As a result, the “regulate flow” and “de-superheat flow” functions of the high pressure turbine bypass valve transition to “degraded”. The status change of the function “de-superheat flow” leads the high pressure turbine bypass valve’s outlet temperature T_{out} to be higher than the designed value. The outlet flow of the high pressure turbine and the high pressure turbine bypass valve are designed to have the same temperature when they mix in Pipe7. Because the outlet temperature of the high pressure turbine bypass valve is higher than the designed value, the inlet temperature of Pipe7 is not uniformly distributed. This situation of unevenly distributed inlet temperature has persisted for $t(T_{in1_P7} \neq T_{in2_P7}) = 1$ time unit which is $\leq t_{cir-cor} = 50$ time unit. Therefore, Pipe7’s mode is “nominal” and its function “transfer flow” is “operating”. Because the feed water pump’s “supply flow” and the condenser’s “condense flow” functions are “operating” the system’s function is “operating”.

At time unit 56 the situation that the inlet temperature of Pipe7 is not uniformly distributed has persisted for $t(T_{in1_P7} \neq T_{in2_P7}) = 51$ time units which is $> t_{cir-cor}$. Therefore, the mode for Pipe7 transitions from “nominal” to “corrosion” and Pipe7’s “transfer flow” function transitions to “degraded”. As the feed water pump’s “supply flow” and the condenser’s “condense flow” functions are “operating” the system’s function is “operating”.

At time unit 57 the corroded material generated in Pipe7 enters the low pressure turbine. The situation of corroded material flowing into the low pressure turbine has persisted for $t(Q_{corrosion_in_LPT} > 0) = 1$ time unit which is $\leq t_{bc-cri} = 5$ time units. Thus, the low pressure turbine’s mode is “nominal” and its functions “generate power” and “de-superheat flow” are “operating”. As the feed water pump’s “supply flow” and the condenser’s “condense flow” functions are “operating” the system’s function is “operating”.

At time unit 58 the corroded material flows into the condenser and the feed water pump. The situation that the corroded material flow $Q_{corrosion_in}$ is greater than 0 for both the feed water pump and condenser has persisted for $t(Q_{corrosion_in_Cd} > 0) = 1$ time unit which is $\leq t_{cc-cri} =$

10 time units, and is $\leq t_{mc-cri} = 20$ time unit. Thus both the condenser and the feed water pump's modes are "nominal" and their functions "condense flow", "supply flow", and "increase pressure" are all "operating". As the feed water pump's "supply flow" and the condenser's "condense flow" functions are "operating" the system's function is "operating".

At time unit 62, the corrosion generated in Pipe7 has continued to flow into the low pressure turbine and the situation has persisted for $t(Q_{corrosion_in_P7} > 0) = 6$ time units which is $> t_{bc-cri}$. As a result, the mode of the low pressure turbine transitions from "nominal" to "blade corrosion". The functions "generate power" and "de-superheat flow" transition from "operating" to "degraded". As the feed water pump's "supply flow" and the condenser's "condense flow" functions are "operating" the system's function is "operating".

At time unit 63, because the low pressure turbine's functions "generate power" and "de-superheat flow" are "degraded" the protection mechanism is triggered and the low pressure turbine valve is closed. As a result, the low pressure turbine's mode transitions from "blade corrosion" to "shut down". Its functions "generate power" and "de-superheat flow" transition from "degraded" to "lost". As the feed water pump's "supply flow" and the condenser's "condense flow" functions are "operating" the system's function is "operating".

At time unit 68, the accumulated time that corroded material has continuously entered the condenser is $t(Q_{corrosion_in_Cd} > 0) = 11$ time units which is $> t_{cc-cri}$. As a result, the condenser's mode transitions from "nominal" to "tube corrosion" and its function "condense flow" transitions to "degraded". Since "condense flow" is one of the system's critical functions, the system's function status transitions to "degraded".

At time unit 78, the accumulated time that corroded material has continuously flowed into the feed water pump is $t(Q_{corrosion_in_FWP} > 0) = 21$ time units which is $> t_{mc-cri}$. As a result, the feed water pump's mode transitions to "motor corrosion" and its functions "increase pressure" and "supply flow" transition to "lost". Since "supply flow" is a critical function of the system, the system's function status transitions to "lost" and the system has lost its functionality.

Table 11 FFIP Demonstration for Fault Propagation in the Turbine Bypass System

Component	P1	P2	HPTV	P4	HP T		P6	P3	HP TBV		P5	P7	P8	LPTV	P10	LP T		P11	P9	LP TBV		P12	P13	CD	P14	FWP		P15	FWV	P16	System	
Function Time	TF	TF	RF	TF	GP	DF	TF	TF	RF	DF	TF	TF	TF	RF	TF	GP	DF	TF	TF	RF	DF	TF	TF	CD	TF	SF	IP	TF	RF	TF	CD SF	
1	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
6	O	O	O	O	O	O	O	O	D	D	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
56	O	O	O	O	O	O	O	O	D	D	O	D	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
57	O	O	O	O	O	O	O	O	D	D	O	D	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
58	O	O	O	O	O	O	O	O	D	D	O	D	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
62	O	O	O	O	O	O	O	O	D	D	O	D	O	O	O	D	D	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
63	O	O	O	O	O	O	O	O	D	D	O	D	O	O	O	L	L	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
68	O	O	O	O	O	O	O	O	D	D	O	D	O	O	O	L	L	O	O	O	O	O	O	D	O	O	O	O	O	O	O	D
78	O	O	O	O	O	O	O	O	D	D	O	D	O	O	O	L	L	O	O	O	O	O	O	D	O	L	L	O	O	O	O	L

P#: Pipe.number; HPTV: High pressure turbine valve; HPT: High pressure turbine; LPTV: Low pressure turbine valve; LPT: Low pressure turbine;
 HP TBV: High pressure turbine bypass valve; LPTBV: Low pressure turbine bypass valve; FWP: Feed water pump; FWV: Feed water valve; CD:
 Condenser; TF: Transfer flow; RF: Regulate flow; GP: Generate power; DF: De-superheat flow; SF: Store flow; CF: Condense flow; SF: Supply
 flow; IP: Increase pressure ; O: Operating; D: Degraded; L: Lost;

The system function status after the leakage injection into the high pressure turbine bypass valve is given in Table 11. As can be seen from the table above, after injected the internal leakage into the high pressure turbine bypass valve, the local effect is the high pressure turbine bypass valve's function transitions to a "degraded" status. The next level effect is the degrade of Pipe7 function. Eventually, the fault injection leads to the system level effect that the whole system loses its functionality.

The FFIP method discussed in this chapter serves as an indicator for the user, in the conceptual design stage, to be aware of what the system's behavior would be after a particular type of fault injection. It helps engineers identify which function(s) will be lost and approximately when. It can also show if safeguards or redundant components are necessary to make the designed system more robust, which would reduce the redesign and maintenance cost in later stages of the development life-cycle.

Chapter 3 Degradation Model for Single Component

3.1 Stress-Strength Interference Model

Chapter 2 discussed a high level method to study a system's behavior caused by a component's failure. This chapter will discuss a low level failure mode model and develop a case study to demonstrate the application of the model.

To examine the reliability of a component the concept of stress-strength interference is introduced. In solid mechanics, stress is used to describe the internal force experienced by material while the strength is a property of a material that describes the ability for a material to withstand load without failure. In reliability engineering the definition of stress and strength are broadened. Stress stands for the degradation of the component, while strength stands for the maximum degradation which that component can withstand without failure. Table 12 contains three applications of the stress-strength interference model.

Table 12 Stress-Strength Interference for Different Failure Modes

Failure Mode	Stress	Strength
Valve internal/external leakage	Actual leakage rate	Acceptable leakage rate
Valve plugged	Actual debris, corrosion	Acceptable debris, corrosion
Solenoid actuator responding slowly	Degraded spring stiffness	Spring stiffness needed to achieve minimum valve response time

Under this model, failure occurs when "stress exceeds strength". Since there are uncertainties in the parameters in the degradation model, the stress and/or strength would each have a probability distribution. Components' failure will occur if the stress increases with time and/or the strength decreases with time. The probability of failure is indicated by the overlap of the probability density functions of stress and strength. This overlap is the interference region. A

large interference region indicates a high probability of failure while a small interference region indicates a low probability. The concept of stress-strength interference is shown in the Figure 11.

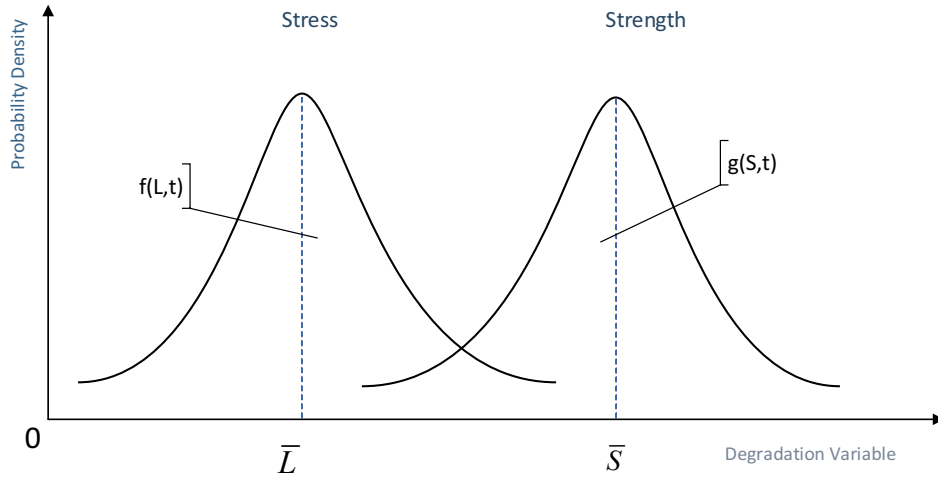


Figure 11 General Stress-strength Interference Illustration

The probability of failure is defined in Equation 2.

$$P(L > S, t) = \int_0^{\infty} f(L, t) \left[\int_0^L g(S, t) dS \right] dL$$

Equation 2

Where:

$f(L, t)$: Stress probability density function

$g(S, t)$: Strength probability density function

t: Time after operation

L: Stress of the component

\bar{L} : Mean of the stress distribution

S: Strength of the component

\bar{S} : Mean of the strength distribution

A special case for the stress-strength interference model is when strength is defined as a threshold rather than a distribution. There are often specific requirements for the performance of components. When monitoring components' performance, components will be classified as healthy while meeting the requirement and will be classified as failed when specific requirements are not met. There may also be multiple thresholds when evaluating components' performance as shown in Figure 12. This concept can be mapped to the component's modes that can be evaluated based on the same degradation variable, e.g. internal leakage and internal rupture are evaluated based on the degradation variable leakage rate.

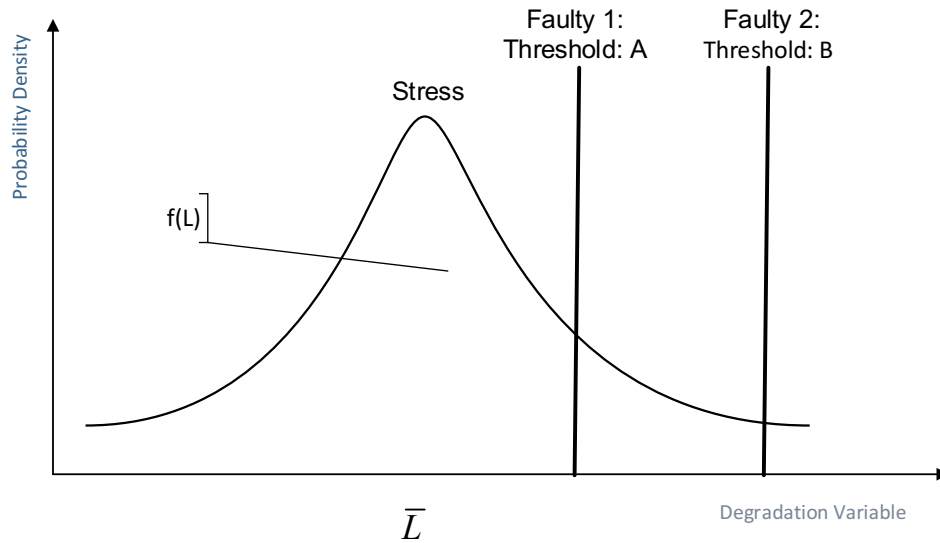


Figure 12 Stress-strength Interference with Constant Thresholds

Then the probability for the component to be in a nominal mode is: $P(L \leq A) = F(A)$; the probability for the component to be at faulty mode 1 is: $P(A < L \leq B) = F(B) - F(A)$, the probability for the component to be at faulty mode 2 is: $P(L > B) = 1 - F(B)$. $F(x)$ is the cumulative distribution function for stress and is defined as $F(x) = \int_0^x f(y)dy$.

It should be noted that the illustrations above use normal distributions for stress and strength to discuss the concept of stress-strength interference, but the actual probability distribution function of stress and strength may be different. The distribution could be a Weibull

distribution, a Gamma distribution, a lognormal distribution or a mixed distribution, whichever fits the data best. The distribution function should be defined on a case by case basis.

3.2 Degradation Model for Single Component

3.2.1 Degradation Model from Literature

To study the probability that a valve could fail due to internal leakage, a stress-strength model was proposed to describe the manner that a valve could fail by Strutt [14]. In Stress-Strength Interference studies for offshore gate valves, Strutt proposed the following degradation model in Equation 3.

$$L(t) = L_0 + \alpha t + (k_1\beta_1 + k_2\beta_2)t \quad \text{Equation 3}$$

Where: Strutt defined the variables as follows.

“ $L(t)$: Age-dependent mean leakage rate.

L_0 : Initial leakage rate

α : Annual increase in leakage rate resulting from corrosion damage to the surface.

β_1 : Mean leakage rate per open-close cycle arising from abrasive wear during actuation.

β_2 : Mean variation in leakage rate per work over the operation as a result of wireline damage.

k_1 : Overall mean frequency of open-close cycles.

k_2 : Frequency of events per year of workovers.

t : Operation time (year).”

*Work over: maintenance and component replacement operation.

The advantage of the proposed model is that it combines valve degradation caused by both natural aging and working conditions. However, the model contains too many parameters that need to be justified, and often there is insufficient information to provide accurate estimation for those parameters’ values [15]. Large uncertainty relates to a large variance of the

estimated stress distribution that could cause failure. Therefore, a more general model is desired to evaluate components' performance.

3.2.2 Modified Degradation Model

The model discussed in the previous section is specifically derived for the internal leakage effect in valves due to aging in the offshore and subsea industry. In the nuclear industry, information is limited, and so a model with fewer parameters is desired. After simplification, the modified degradation model is shown in Equation 4.

$$L(t) = L_0 + a * t + \frac{b * t}{12N} \sum_{n=1}^N [w(n) * k(n)], \quad N = \text{floor}\left(\frac{t}{12}\right) \quad \text{Equation 4}$$

, where a: Rate of degradation due to natural wear. (1/month)

b: Rate of degradation due to accumulating demands. (1/demand)

$k(n)$: Demands on n-th year. (demand)

$w(n)$: Demand weighting factor.

t: Time in service. (month, integer)

N: Time in service. (year, integer)

L: Expected value for the degradation.

L_0 : Initial degradation.

In the degradation model derived from the reference [12], it is assumed that the demand for the offshore valve remains constant. This is not necessarily true for the nuclear power plant. Thus, the model has been modified as shown above.

In the traditional nuclear power plant the demand for the turbine bypass system is low [17], thus taking the average demand for one year is more reasonable than using the record of demands for the past month, which is likely to be 0.

3.2.3 Leakage Failure Model

In this section the model developed in Equation 4 is applied to the case of internal leakage in a valve.

For this application, it is assumed that there is no initial leakage, and parameters a and b follow normal distributions. However, the actual distributions for those parameters have not been determined and could be other distributions as well.

$$a \sim N(\mu_a, \sigma_a^2); b \sim N(\mu_b, \sigma_b^2) \quad \text{Equation 5}$$

The variance for the leakage degradation is a time-dependent variable.

Let us assume that a and b are independent parameters, and that the demand for the turbine bypass valve follows a discrete uniform distribution. Let us also assume all past demands have the same cumulative effect on the degradation, thus $w(n) = 1, \forall n \in N$.

The probability density functions for a and b and the probability mass function for k are defined as shown in Equation 6. Equation 7 describes the variance and mean the a , b and k .

$$f_a = \frac{1}{\sigma_a \sqrt{2\pi}} e^{-\left[\frac{x_a - \mu_a}{\sqrt{2}\sigma_a}\right]^2}; f_b = \frac{1}{\sigma_b \sqrt{2\pi}} e^{-\left[\frac{x_b - \mu_b}{\sqrt{2}\sigma_b}\right]^2}$$

$$f_{k(n)} = \begin{cases} \frac{1}{k_{high} - k_{low} + 1}, & k(n) \in [k_{low}, k_{high}], \forall n = 1, N \\ 0 & \text{else} \end{cases} \quad \text{Equation 6}$$

$$\text{var}(b) = \sigma_b^2; \text{var}(k(n)) = \left(\frac{(k_{high} - k_{low} + 1)^2 - 1}{12} \right) \quad \text{Equation 7}$$

$$E(a) = \mu_a; E(b) = \mu_b; E(k(n)) = \frac{(k_{high} + k_{low})}{2}$$

The expected value for leakage rate is described in Equation 8.

$$\begin{aligned}
E(L) &= E\left(a * t + \frac{b * t}{12N} \sum_{n=1}^N [k(n)]\right) \\
&= E(a * t) + E\left(\frac{b * t}{12N} \sum_{n=1}^N [k(n)]\right) \\
&= t\mu_a + E\left(\frac{b * t}{12N}\right) E\left(\sum_{n=1}^N [k(n)]\right) \\
&= t\mu_a + \frac{t\mu_b}{12N} \sum_{n=1}^N E(k(n)) \\
&= t\mu_a + \frac{t\mu_b}{12N} \sum_{n=1}^N \frac{(k_{low} + k_{high})}{2} \\
&= t\mu_a + \frac{t\mu_b}{24} (k_{low} + k_{high})
\end{aligned} \tag{Equation 8}$$

Since the demands at each year are assumed to be independent with each other. All parameters a,b, and k are assumed to be uncorrelated. Thus the variance can be determined shown in Equation 9 below.

Thus we can determine the variance for L shown in Equation 9.

$$\begin{aligned}
var(L(t)) &= var\left(a * t + \frac{b * t}{12N} \sum_{n=1}^N [k(n)]\right) = var(a * t) + var\left(\frac{b * t}{12N} \sum_{n=1}^N [k(n)]\right) \\
&= t^2 var(a) + \left(\frac{t}{12N}\right)^2 var\left(b * \sum_{n=1}^N [k(n)]\right) \\
&= t^2 \sigma_a^2 + \left(\frac{t}{12N}\right)^2 var\left(b \sum_{n=1}^N [k(n)]\right)
\end{aligned} \tag{Equation 9}$$

Where,

$$\begin{aligned}
& \text{var} \left(b * \sum_{n=1}^N [k(n)] \right) \\
&= [E(b)]^2 \text{var} \left(\sum_{n=1}^N [k(n)] \right) + \left[E \left(\sum_{n=1}^N [k(n)] \right) \right]^2 \text{var}(b) + \text{var}(b) \text{var} \left(\sum_{n=1}^N [k(n)] \right) \\
&= [E(b)]^2 \sum_{n=1}^N \text{var}(k(n)) + \left[\sum_{n=1}^N E(k(n)) \right]^2 \text{var}(b) + \text{var}(b) \sum_{n=1}^N \text{var}(k(n)) \\
&= \mu_b^2 \sum_{n=1}^N \left[\frac{(k_{high} - k_{low} + 1)^2 - 1}{12} \right] + N^2 \left[\frac{k_{high} + k_{low}}{2} \right]^2 \sigma_b^2 + \sigma_b^2 \sum_{n=1}^N \left[\frac{(k_{high} - k_{low} + 1)^2 - 1}{12} \right] \\
&= \mu_b^2 N * \frac{(k_{high} - k_{low} + 1)^2 - 1}{12} + N^2 \left[\frac{k_{high} + k_{low}}{2} \right]^2 \sigma_b^2 + \sigma_b^2 N * \frac{(k_{high} - k_{low} + 1)^2 - 1}{12} \\
&= N * \frac{(k_{high} - k_{low} + 1)^2 - 1}{12} (\mu_b^2 + \sigma_b^2) + N^2 \left[\frac{k_{high} + k_{low}}{2} \right]^2 \sigma_b^2
\end{aligned}$$

Thus,

$$\begin{aligned}
& \text{var}(L(t)) \\
&= t^2 \sigma_a^2 + \left(\frac{t}{12N} \right)^2 \text{var} \left(b \sum_{n=1}^N [k(n)] \right) \\
&= t^2 \sigma_a^2 + \left(\frac{t}{12N} \right)^2 \left\{ N * \frac{(k_{high} - k_{low} + 1)^2 - 1}{12} (\mu_b^2 + \sigma_b^2) + N^2 \left[\frac{k_{high} + k_{low}}{2} \right]^2 \sigma_b^2 \right\}
\end{aligned}$$

Analytically solving the distribution could be difficult, especially for more complicated distribution cases. Since analytically solving the distribution is undesirable, the mixture distribution can be expressed using Monte Carlo simulation.

Note that by dividing the present degradation by maximum allowable degradation the model is nondimensionalized. The benefit of having a dimensionless model is the convenience of future adjustment. For instance, the model above indicates that the leakage rate has a linear relationship with operation time, given the operation frequency is constant. However, if the experimental and/or published reliability data disagree with a linear relationship, the right-hand

side of the Equation 4 can be adjusted to log scale or exponential scale to match experimental and/or published data.

3.4 Case study for internal valve leakage

3.4.1 Model description

This section will illustrate how to implement the model. Parameters for the distributions are assumed to be what is shown in Table 13.

Table 13: Value Specification for the Degradation Model

$\mu_a = 3 * 10^{-4}(1/month)$	$\sigma_a^2 = 7 * 10^{-5}(1/month)^2$
$\mu_b = 2 * 10^{-4}(1/demand)$	$\sigma_b^2 = 2 * 10^{-5}(1/demand)^2$
$k_{low} = 10(demand)$	$k_{high} = 50(demand)$

For the case study, the valves are only considered to be either healthy or failed. Additional status implemented, however, for simplicity, they are not considered in this case study.

The total population of valve samples is 500. Because the model has been nondimensionalized the threshold for internal leakage to indicate components' failure is 1. (Correspond to the thresholds such as A and B in Figure 12)

3.4.2 Simulation results

The Monte Carlo simulation result is shown in Figure 13.

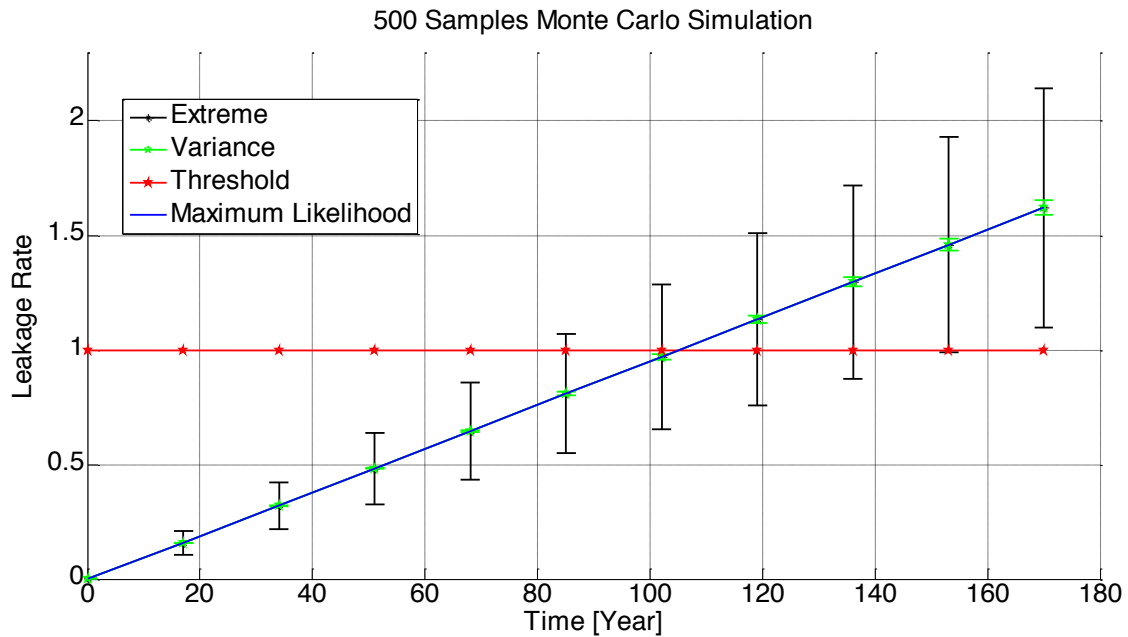


Figure 13 Leakage Degradation Simulation for 500 Samples

As shown above once the actual degradation exceeds the threshold the status of the component would be defined as failed. The estimated degradation value (blue line in Figure 13), is where \hat{a} and \hat{b} are the mean value calculated using the maximum likelihood method to fit the 500 samples, and \hat{k} is the mean of the maximum and minimum observation.

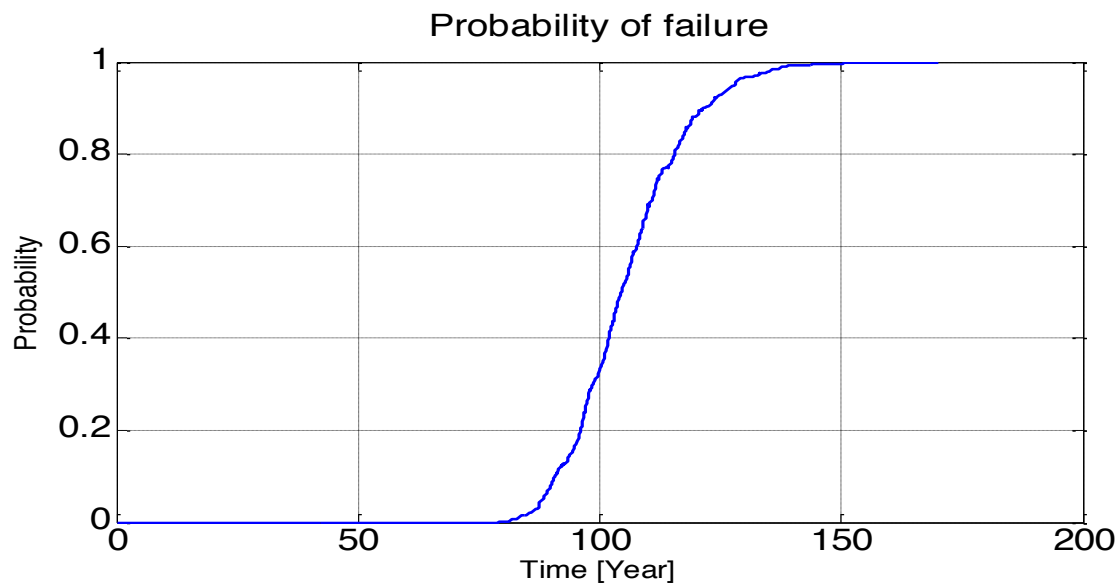


Figure 14 Probability of Failure

Figure 14 indicates that before 80 years it is rare for components to fail due to leakage. The probability starts to increase at around 80 years and after operation of about 150 years, the probability for the component to fail is near 1. This indicates that almost no components can withstand the degradation and still be functional after 150 years.

3.4.3 Results discussion

Since L is a mixed distribution, it is desirable to learn the characteristics of the distribution based on simulation results. Examining the difference between mean and median is an approach that can be used to study the symmetry properties of a distribution.

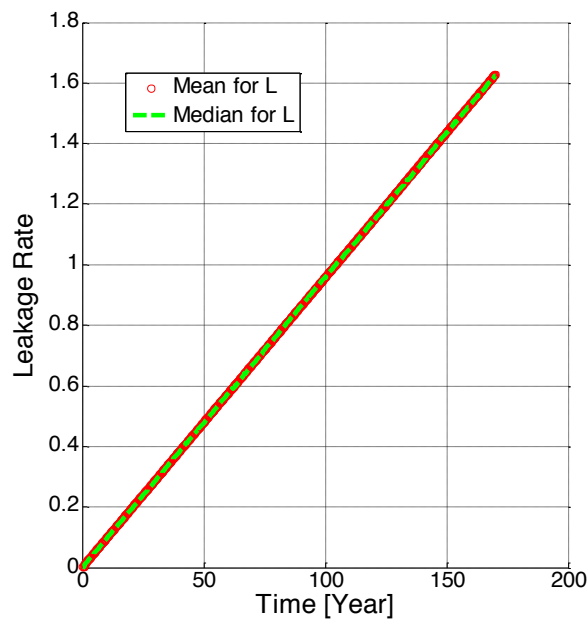


Figure 15(a) Mean and Median for Degradation

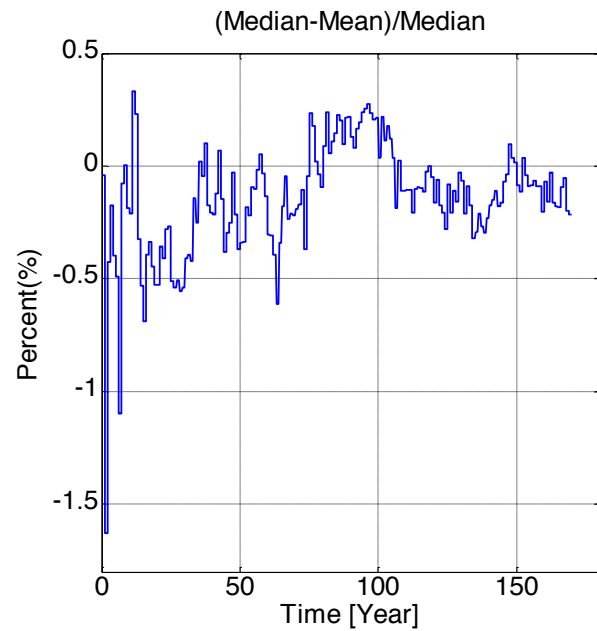


Figure 15(b) Percent difference between Mean and Median

Figure 15 indicates that the mixed distribution for L is nearly but not entirely symmetric since the mean and median value are close (b), but with a slight difference. It also indicates that the mean and median increase linearly with time.

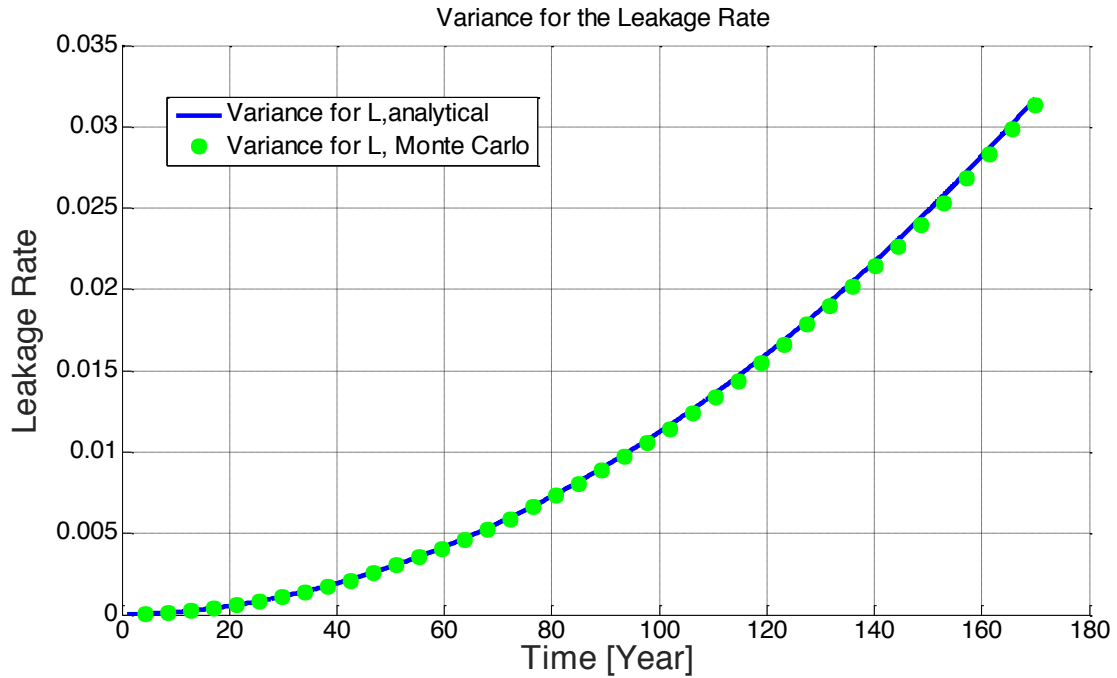


Figure 16 Variance for the Degradation

Figure 16 indicates that, unlike mean and median, the variance of the degradation increases nonlinearly with time.

Figure 17 presents the probability distributions of the leakage rate at 5 evenly spaced time intervals within the simulation time.

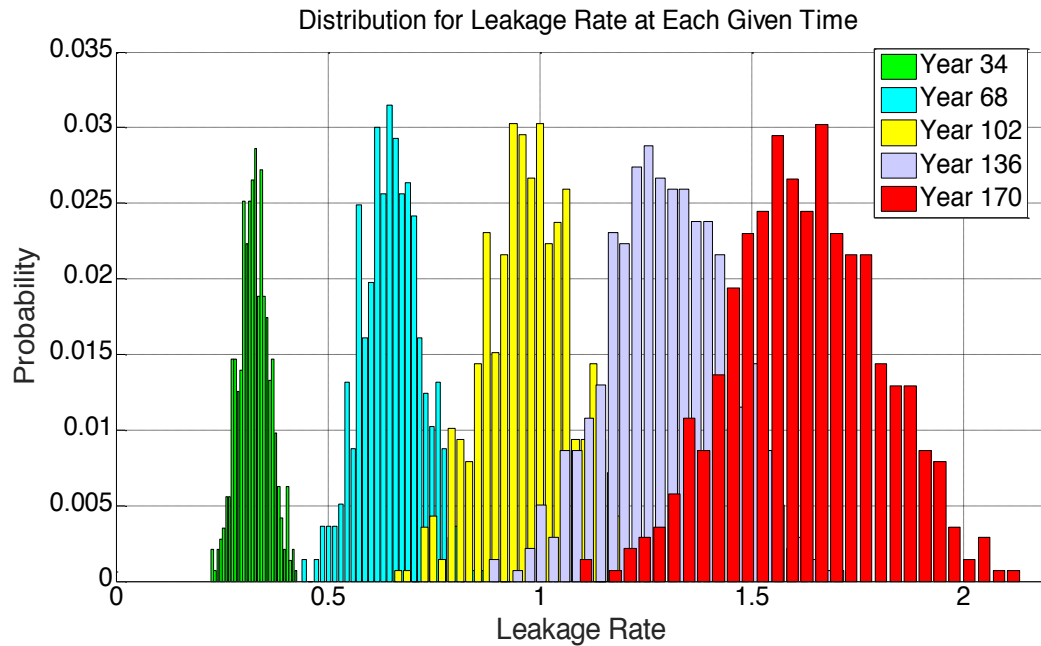


Figure 17 Distribution for Leakage Rate at Each Given Time

As can be seen from the figure above, the distribution's deviation increases with time.

To investigate how the leakage rate distribution would fit some common distributions, tests of fit were performed using 16 candidate distribution models. The top 3 fitting results are shown in Table 14. Detailed fitting results are shown in Appendix.

Table 14 Test of Fit at 5 Selected Times

	Distribution Type	AD	P
Year 34	Normal	0.113	0.992
	3 parameter Weibull	0.221	>0.500
	Gamma	0.337	>0.250
Year 68	Normal	0.136	0.978
	Lognormal	0.584	0.128
	Gamma	0.291	>0.250
Year 102	Normal	0.237	0.786
	Gamma	0.500	0.222
	Logistic	0.492	0.177
Year 136	Normal	0.174	0.927
	3 parameter Weibull	0.305	>0.500
	Gamma	0.309	>0.250
Year 170	Normal	0.187	0.904
	3 parameter Weibull	0.323	0.471
	Gamma	0.263	>0.250

In the tests of fit run by Minitab, a lower Anderson-Darling (AD) value suggests that the data fits the distribution better, and higher P value suggests that the null hypothesis is not rejected. The null hypothesis is that the data follows the specified distribution. If the AD value exceeds the given critical value shown in Table 15 [16], the null hypothesis is rejected with certain significance levels. If the P value is great than 0.05, then we can conclude that there is little or no evidence to reject the null hypothesis.

Table 15 Critical Value for Anderson-Darling Test (Mean and Median Unknown)

	Significance level				
	Distribution	10%	5%	2.50%	1%
Critical Value	Normal	0.656	0.787	0.918	1.092
	Lognormal	0.656	0.787	0.918	1.092
	Gamma	0.631	0.752	0.873	1.035
	Weibull	0.637	0.757	0.877	1.038

From Table 14 and Table 15, normal distribution can represent the data properly. The null hypothesis is not rejected.

It is also desired to investigate what the distribution of the time to failure would be for components in the sample data. The tests of fit results are shown in Table 16 and Figure 18. The critical value for Anderson-Darling test are shown in Table 15.

Table 16 Test of Fit for the Time to Failure

Distribution Type	AD	P
Lognormal	0.681	0.0075
Loglogistic	0.707	0.039
3-parameter Lognormal	0.239	*
3-parameter gamma	0.260	*

Note: * indicates the P value for the 3-parameter distribution cannot be calculated.

As can be seen from Table 16, the time to failure data can be represented by a 3 parameter gamma, a 3-parameter Weibull, or a lognormal distribution.

As can be seen Figure 18, the 3-parameter distributions fit the data better. However, the industry standard does not use a 3-parameter distribution model in their databases due to the complexity [17]. Thus, a two parameter lognormal distribution can be assumed for the time to failure for valves. In the component reliability database, a gamma distribution is used to represent the time to failure due to internal leakage for valves in general. [18]. To better match industry databases in future work, the model needs to be modified accordingly.

Distribution Fit for Time to Failure

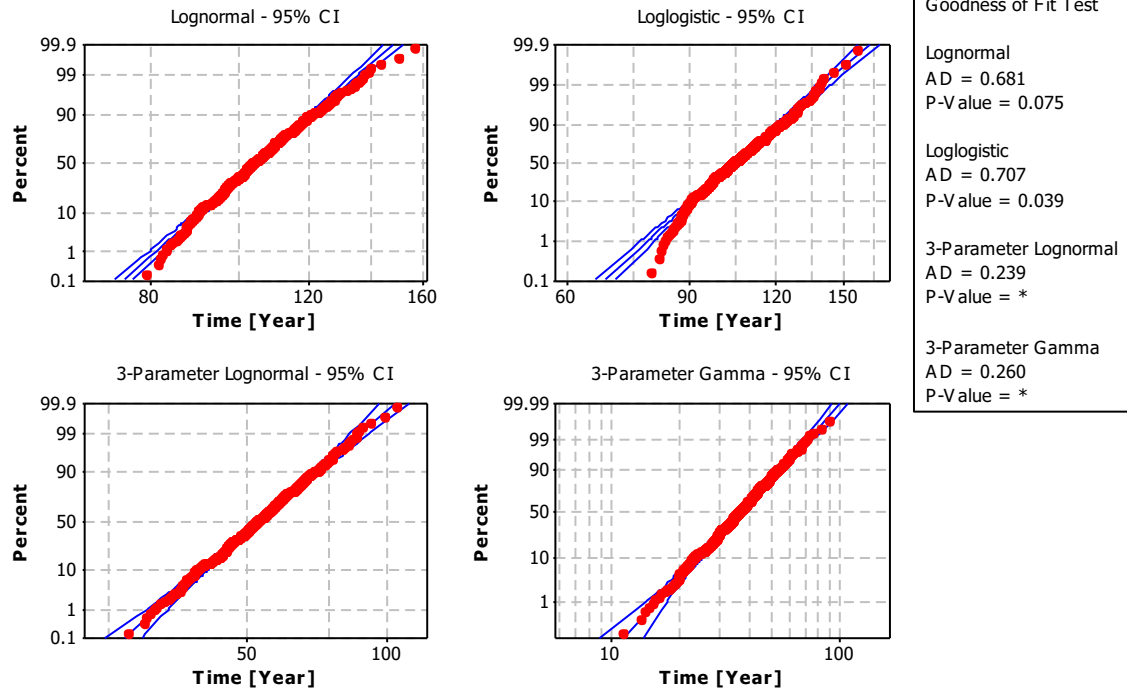


Figure 18 Distribution Fit for Time to Failure

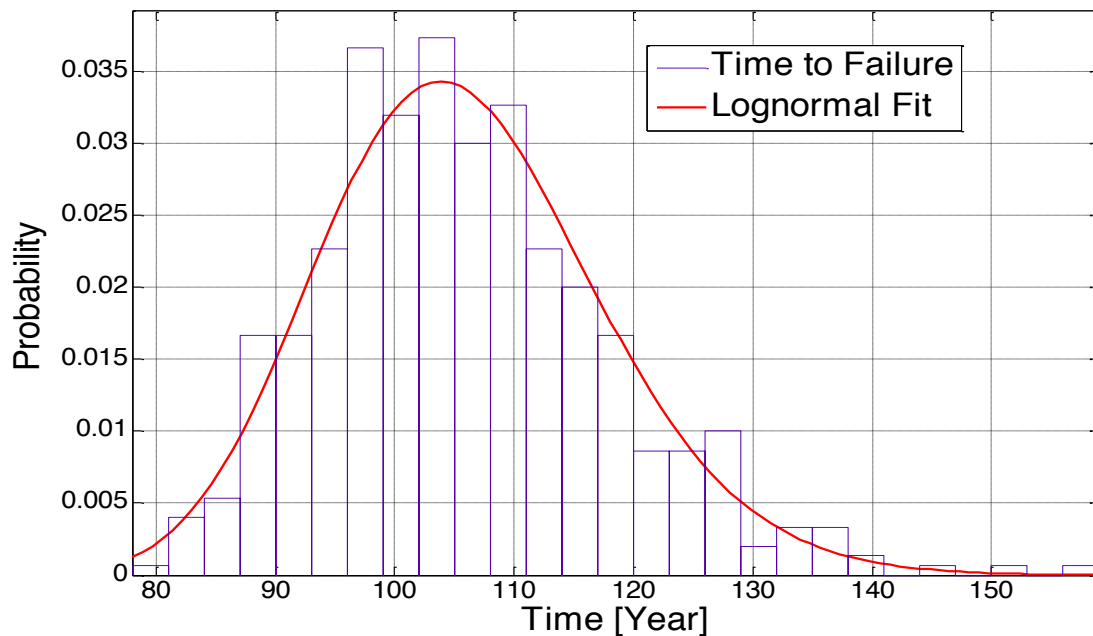


Figure 19 Lognormal Fit for Time to Failure

Figure 19 shows the lognormal fit for the time to failure data. It should be noted that unlike the leakage rate at a given time. The time to failure is not a symmetrical distribution.

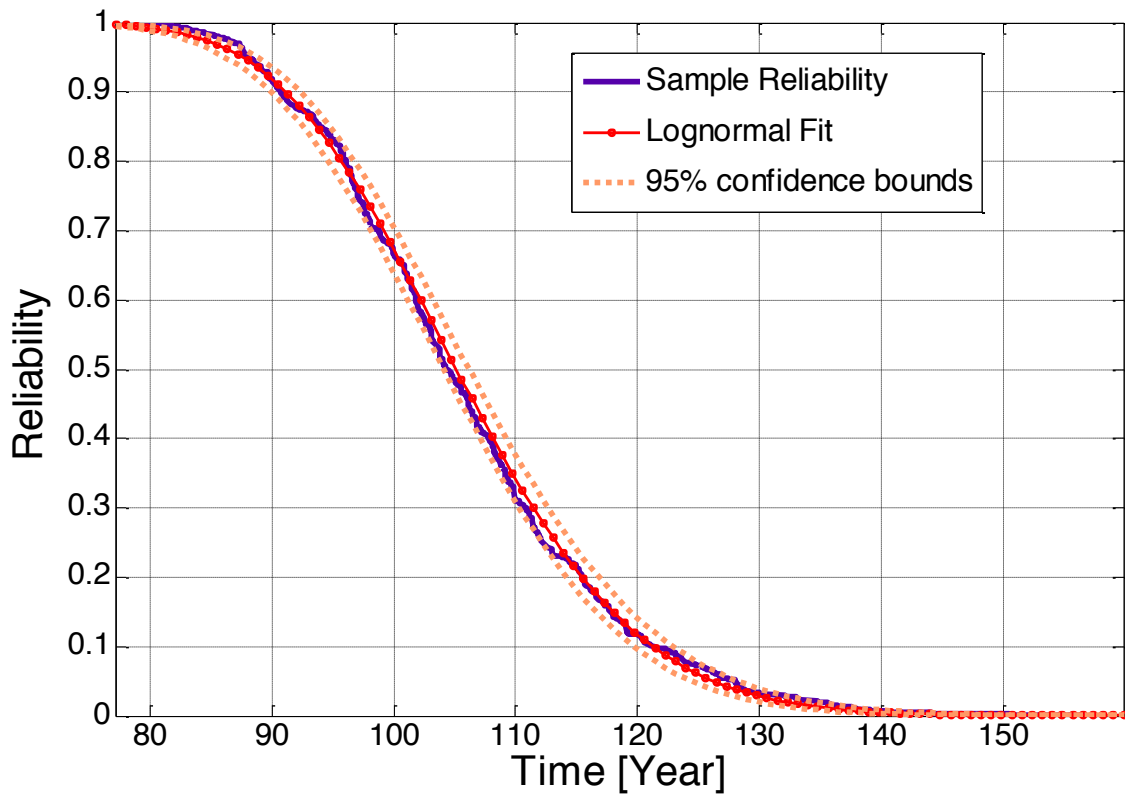


Figure 20 Lognormal Distribution Fit for the Sample Reliability Function

As can be seen from Figure 20, the lognormal distribution fits the reliability function constructed by the time to failure data well. However, it should be noted that due to the relatively small population used for the Monte Carlo simulation, the fit results could vary.

The time to failure determined by the model discussed in this chapter can be used to specify the time units used to describe a component transition time between different modes as was discussed in Chapter 2. For example, it can determine how long it takes for a valve to transition from a “nominal” mode to a “internal leakage” mode. It can also determine the transition time between different faulty modes such as “internal leakage” and “internal rupture”.

Chapter 4 Conclusion and Future Work

In this thesis, Chapter 2 discussed FFIP, a high level fault propagation method for hardware components which describes the system's behaviors caused by certain types of failure modes. FFIP helps engineers in the conceptual design stage to identify function loss in the designed system, and locate when the loss occurs. Behavioral rules and functional failure logic for components of interest in a turbine bypass system in the secondary loop in a nuclear power plant in a nuclear hybrid energy system are developed. The method is demonstrated through injection of a failure mode, an internal leakage, in the high pressure turbine bypass valve. Results show the failure mode can eventually cause the entire system to lose its functionality. Chapter 3 discussed a degradation model that combines the effect of natural aging and demand frequency. The degradation model is combined with the stress-strength interference model to evaluate when components would fail due to a particular failure mode. A case study for valve leakage is demonstrated using the model. Tests-of-fit showed that the model needs to be further modified to match the distributions found in industry standard databases to enable future research.

To provide a more accurate representation of the system, potential future work includes the following: the high level fault propagation analysis can be updated to include software faults and human error as well. Combining hardware faults, software faults, and human errors can help the designer develop a clearer vision of the proposed system design and determine if redundancies are necessary to make the designed system more robust. For the low level degradation model, the turbine bypass line demand could be modeled based on the estimated availability of renewable energy. This could help model the degradation effects of the components more accurately.

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Appendix

Probability Plot for the 34 Year

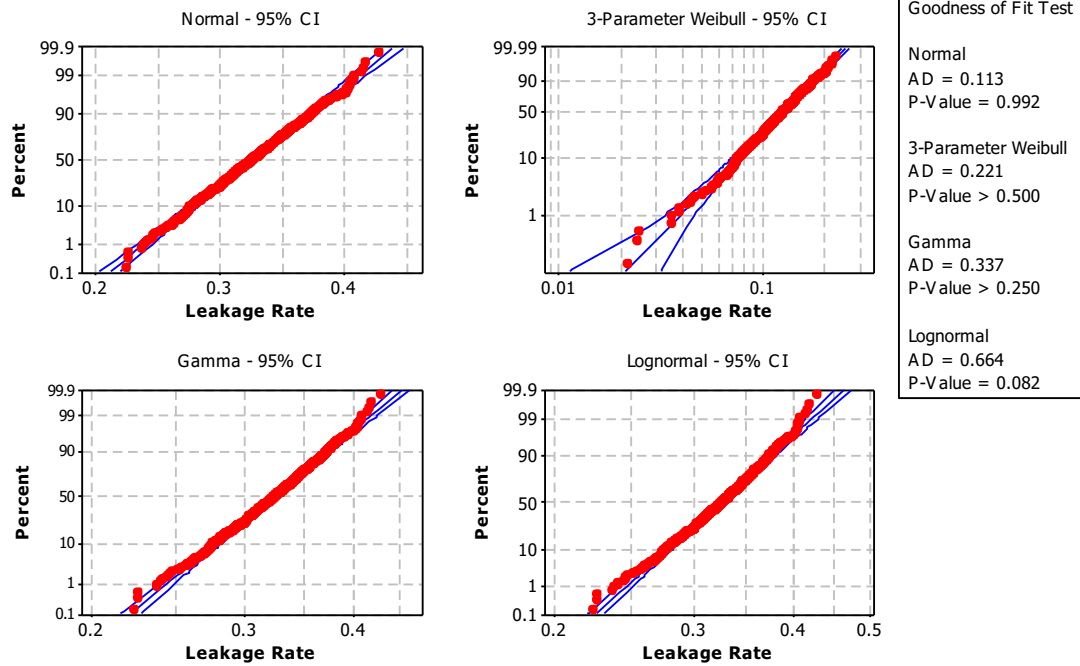


Figure 21 Distribution Fit at the 1st Selected Time

Probability Plot for the 68 Year

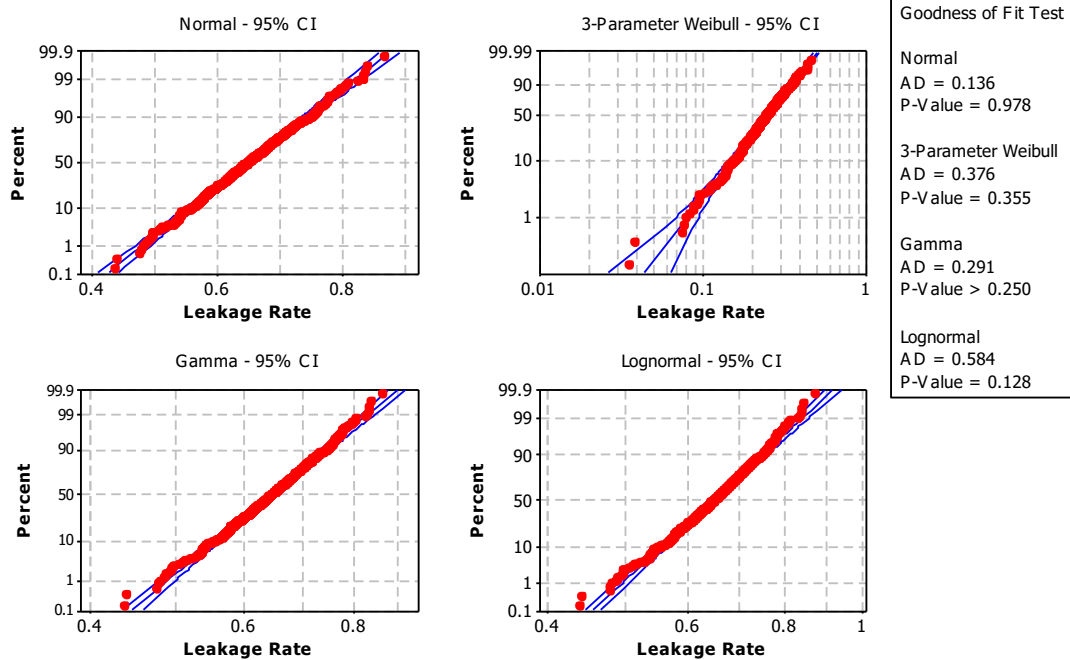


Figure 22 Distribution Fit at the 2nd Selected Time

Probability Plot for the 102 Year

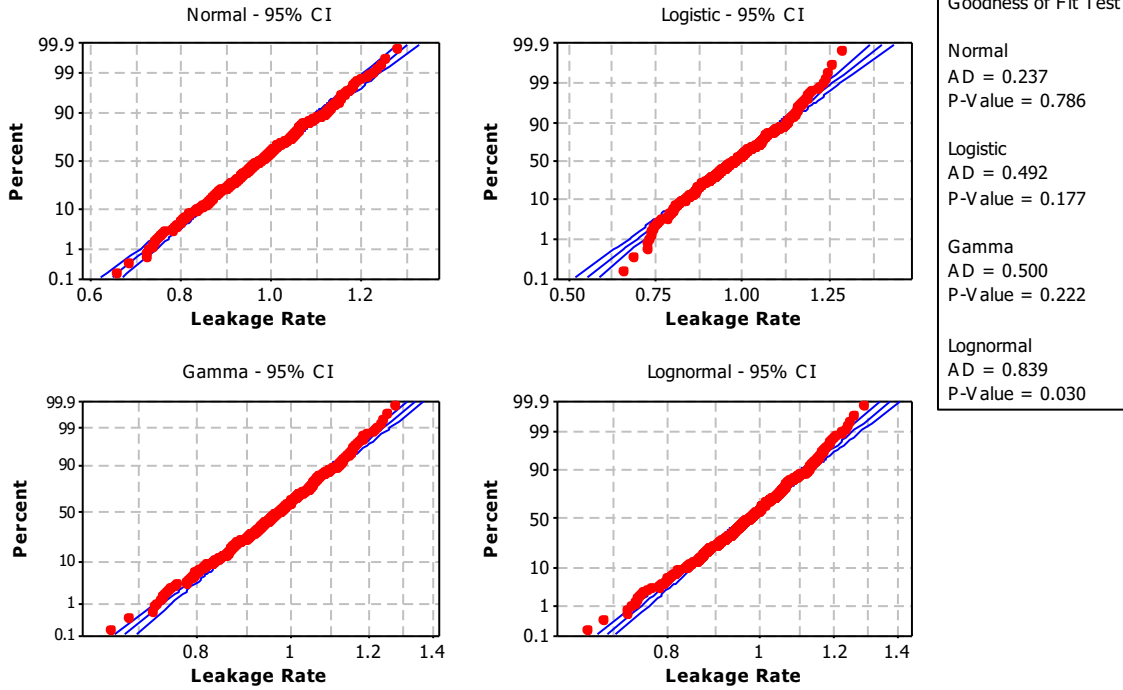


Figure 23 Distribution Fit at the 3rd Selected Time

Probability Plot for the 136 Year

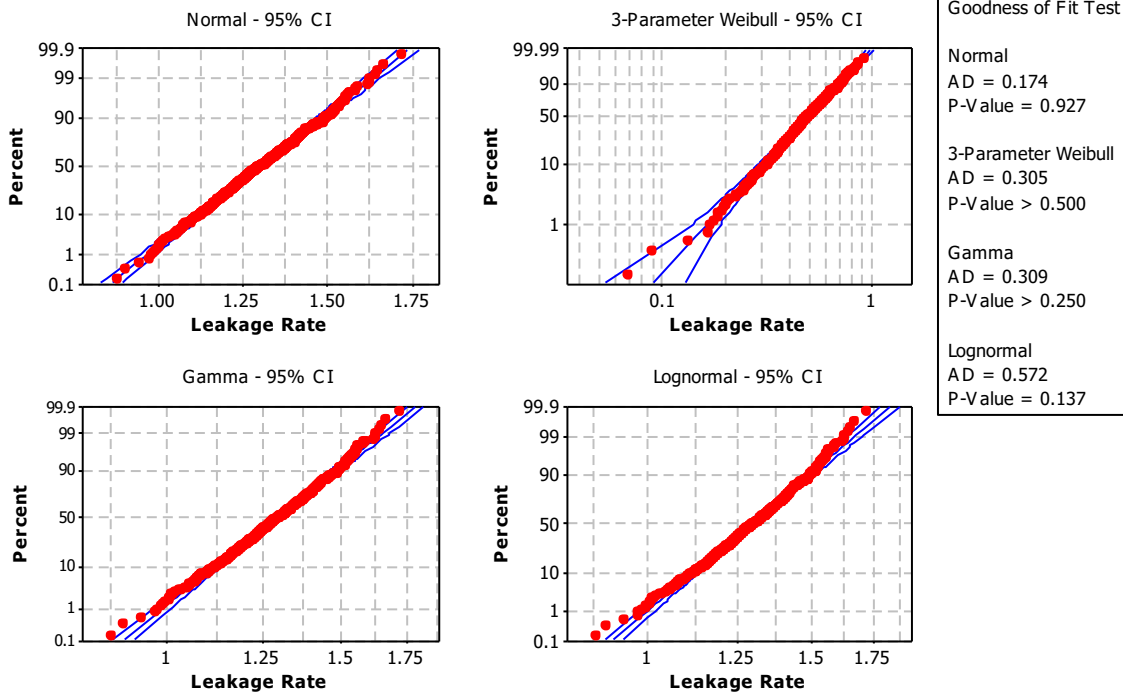


Figure 24 Distribution Fit at the 4th Selected Time

Probability Plot for the 170 Year

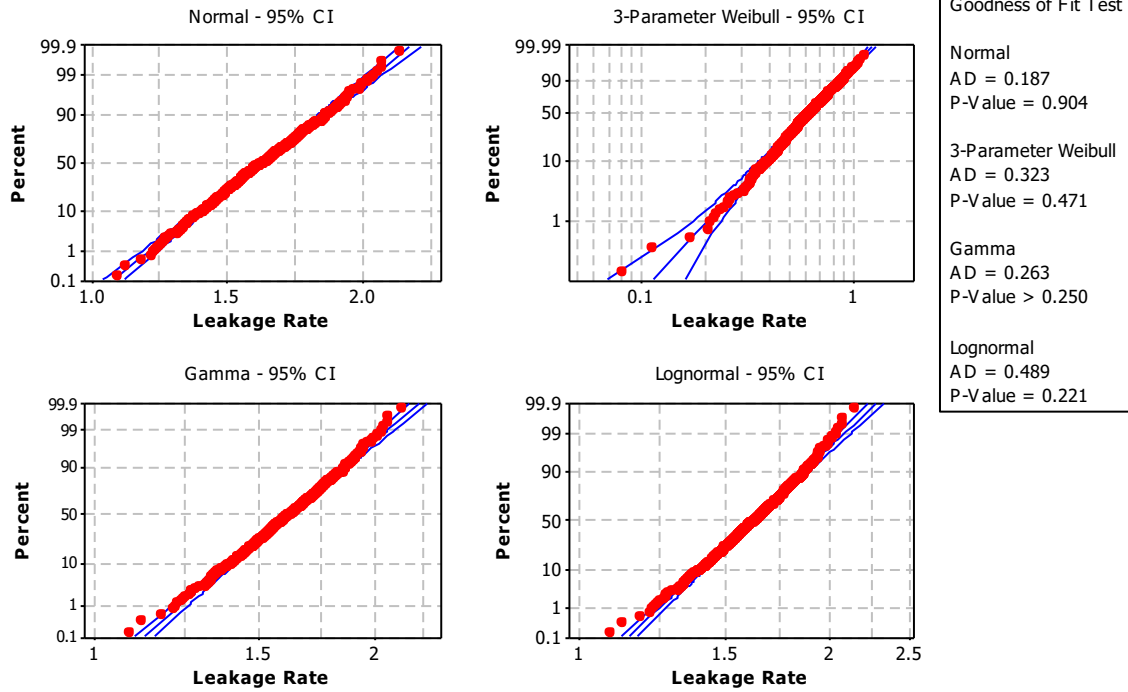


Figure 25 Distribution Fit at the 5th Selected Time